JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 10, No. 11, November 2008, p. 2864 - 2869

Experimental study of ultrasound propagation in granular media

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In this paper we present the experimental results which are concerned by the propagation of ultrasound waves through a granular medium. The acoustic excitation is realized with transducers and the analysis it made in time-frequency domain. The experiments realized show that the detected acoustic signals are very different according to the polarization of the acoustic excitation and detection. In the low-frequency domain the spectroscopy of the transmitted impulses gives rise to peaks the existence and the origin of which are discussed.

(Received September 1, 2008; accepted October 30, 2008)

Keywords: Granular media, Ultrasound propagation

1. Introduction

Ultrasounds propagation in granular media is a complicated process due to technological and natural context and also to their potential to study the properties of the medium through which they propagate. In granular materials, photoelastic visualization and simulation experiments showed that contact forces that appear as a result of extern stresses action are distributed inhomogeneous forming a chains array of (contact) forces. These determine most mechanical properties of uni or bidimensional dense, granular media such as the ability of standing an extern load, nonlinear elastic response and the behavior at flow. At low frequencies where the wavelength is proportional to the magnitude forces chain, the granular medium behaves as a continuous and homogenous one at ultrasounds propagation. At high frequencies, when the wavelength is proportional to the grain size, the scattering effects caused by the spatial fluctuations of the forces chain become significant [1,2].

Experimental researches made in different laboratories showed that classical examination techniques with ultrasounds doesn't give sufficient information (there are presented the amplitude, attenuation and time of the flight). Thus, ultrasonic waveform visualization becomes necessary in order to identify complex characteristics of dense, granular media. At this level of analysis, more sophisticated algorithms and procedures could be used in order to process the obtained data. This kind of algorithms could include the comparison of amplitudes of two or more zones of the waveform on the gate, the comparison of the signal level with DC level, the relative amplitude of two or more peaks, the frequency spectrum (the frequency domain).

Due to extremely high attenuation of ultrasound by air, its transmission in a test medium is done by physically coupling the transducer to the test medium. Therefore, all conventional ultrasound techniques are based upon the severe limitation of a physical contact between the transducer and the test medium by a liquid gel.

A number of granular materials sensitive to liquid contact could be tested for the measurements of thickness, density, mechanical properties, defect detection, etc. This is significant in assuring materials quality and process control, and for cost effective production. The development of non-contact transducers (NCT) mode would allow many more useful applications of ultrasound. For example, with NCT, the characteristics of porous and hygroscopic materials could be determined. The air-coupled ultrasonic investigation is a very attractive method because avoids the disadvantages of the coupling liquid (water, squinter, immersion technique) or coupling paste [3].

2. Theory of the contact sphere

The granular mechanics literature also contains a few constructive algorithms. The dropping method (see Figure 1), suggested for 2D assemblies of circular grains by Bagi in [4], can be considered as a two-dimensional version of the sedimentation algorithm. The required domain is filled up starting from the bottom, always adding one particle at a time to the already existing set of grains. The geometrical position of the actual new particle is defined in such a way that it would exactly touch two previous particles beneath; or perhaps any of the walls of the domain (with no overlaps with other particles). The new particle is placed on the (a) (b) (c) Figure 1. The dropping method: (a) the general idea of the algorithm; unstable (b) and stable (c) position of a new grain previous ones so that if the previous grains are assumed to be fixed with no displacements, the new grain would be in a stable position upon application of a downwards force (see Fig. 1c)

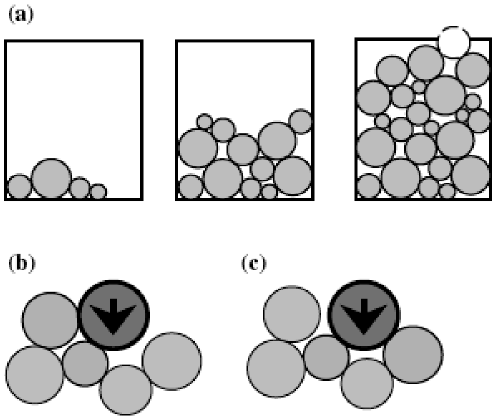


Fig. 1 Dropping method.

A vibrating couple between the sample (grains) and the transducer is inevitable stimulated at the sample-transducer interface and it allow to explain the change of the frequency determined experimentally.

Vibrating modes of the isotropic sphere are classified in two types according to the seismological notation for Earth free oscillations.

While for spherical methods ${}_qS_n$ one has radial movements, the troidal method ${}_qT_n$ doesn't have this kind of movement. The anterior notation includes *q* in the sense of radial order corresponding to the number of surface nodes within the sphere, while the second system correspond to the number of nodal lines on the sphere surface (this is n for ${}_qS_n$ and n-1 for ${}_qT_n$).

The observed magnitude of the frequency change could be shown only by vibrating couple mode The intrinsic angular frequency $\omega(2\pi f_0)$ is defined for the free oscillation state characterized by $k_s = 0$ or by $F = 0$. Thus, one have:

$$\omega_0^2 = \frac{2k}{m} \tag{1}$$

where m and k are the mass and the elastic constant of the simplified system.

The model of proper vibration is reduced to a harmonic oscillator, the elasticity constant k corresponds to the sample intrinsic elasticity and the reduced elasticity constant k_s corresponds to the extrinsic properties around the contact region between the sample and the transducer, as it is shown in Figure 2.

Then, the effect of the reduced elasticity k_s is added to the system and one obtain:

$$\omega^2 = \frac{2k + k_s}{m} = \omega_0^2 + \frac{k_s}{m} \tag{2}$$

for the bonding state characterized by k_s which has to be a function of F by the elastic contact between the sample and the transducers. This is the importance of the vibrating couple model.

The reduced elasticity constant k_s is a model of the elastic properties around the contact region between the sample and the transducers.

The distance x between the two spheres centers decreases with the applied force F(Figure3). The contact surface having the diameter of 2a is formed at the interface of the two spheres due to their elastic deformation.

According to the theory of the contact sphere, the distance between two spheres, x, varies with F as it follows:

$$\Delta x = -g(\upsilon, Y, R) F^{\frac{2}{3}} \tag{3}$$

where the factor g is a function of Poisson ratio υ, the coefficient of Young Y and the radius of curvature R. The contact surface A is written as:

$$A = h(\upsilon, Y, R) F^{\frac{2}{3}} \tag{4}$$

As long as one doesn't disturb the coupling state between the sample and the transducer, one can attribute constant values to g and h during F modulation

At first, one considers the case of the model ${}_0S_0$ characterized as a normal movement of the sample surface. In this case, the modeled elasticity constant is given by:

$$k_s = -\frac{dF}{dx} = \frac{3}{2} g^{-1} F^{\frac{1}{3}} \tag{5}$$

Thus, one has the relation:

$$k_s \propto F^{\frac{1}{3}} \tag{6}$$

By combining (2) with (6), one obtain:

$$\Delta\omega^2 = \omega^2 - \omega_0^2 \propto F^{\frac{1}{3}} \quad \text{or}$$

$$\Delta f^2 = f^2 - f_0^2 \propto F^{\frac{1}{3}} \tag{7}$$

The characteristics of the model T are completely different from the ones of the models S; models T don't include the normal movement of the surface. Thus, a few changes are necessary for models T because the elastic constant of the arc k_s corresponds to the tangential movement between the sample and the transducer. It could be convenient to assume that k_s is proportional to the contact surface A, between the sample and the transducer.

The theory of the contact sphere [5] shows that A is proportional to $F^{\frac{2}{3}}$. Thus, one can expect that:

$$\Delta\omega^2 \propto k_s \propto F^{\frac{2}{3}} \tag{8}$$

for models T.

Models S, excepting ${}_0S_0$ are constitute by two movement at the surface: normal and tangential. This is why it is difficult to theoretically determine the operating form. A review of the experimental observations becomes necessary.

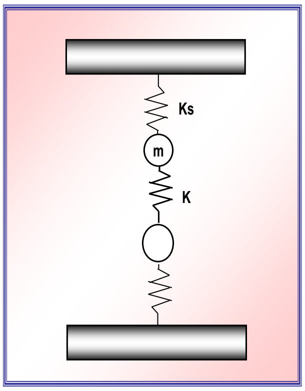


Fig. 2. Vibrating couple.

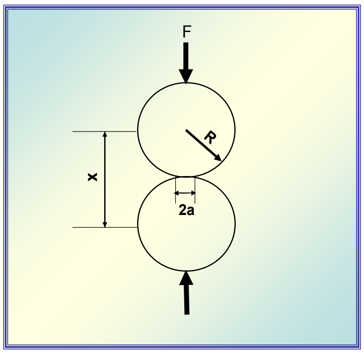


Fig. 3. Contact surfaces.

The model of vibrating couple explains clearly the change caused by the modulation of the clamping force. The phenomenon is almost similar to the chain effect recognized in ultrasonic wave measurements because both problems are caused by the transfer of the vibrating energy.

The desire is to accentuate the following three notations for the purpose of accuracy and efficiency:

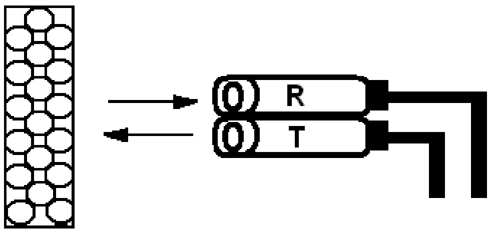
1. The models ${}_0S_0$ and T are special ones made only for the spherical elastic and isotropic sample. If the sample is not spherical or physical properties are not isotropic, proper vibration modes represent combinations of normal and tangential surface movements. Thus, the mean of models 1/3 and 2/3must be universally recommended for the purpose of conducting the correction of the resonance frequency;

2. The sample and the transducers must be well cleaned. If the surface is contaminated with oily substances, one can notice substantial changes of frequency even at negative clamping force. This doesn't surprise because the grease can keep a substantial contact between the sample and the transducers, opposite to the stress force.

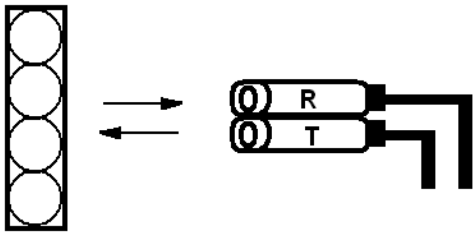
3. The experiment

The two samples consist of two systems made of 11 steel beads of 6.36 mm diameter and 30 glass beads of 4 mm diameter, respectively. Both bead systems are introduced in a glass cylindrical device of 10.6 mm diameter. One considers that the deposition of grains is gravitational and the grains fit perfectly as in a container finding their equilibrium position under the gravitational force. The granulometry distribution is different for both systems: in the case of the beads made of steel, they are arranged in an one-dimensional chain and in the case of the bead made of glass, their arrangement is three-dimensional.

The general form of a data acquisition and processing system consists of an ultrasonic pulses generator, a receiver, an A/D converter with a high digitization rate and a software for experimental data processing [6]. The transducers are non-contact ones and they are positioned in air at 70 mm distance from de sample. Pulse-echo technique is used here (see Figure 4,a glass, b steel)



a
Glass beads system



b

Steel beads system

Fig. 4. System beads and non-contact transducers.

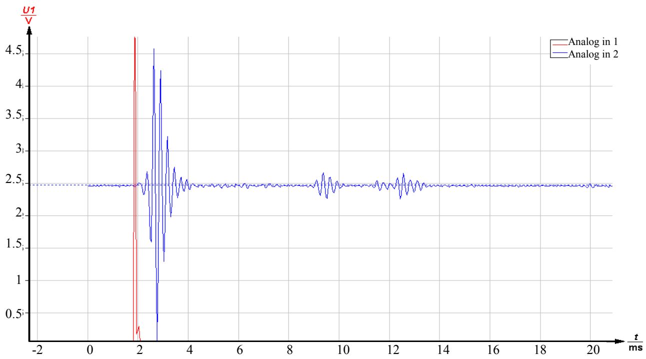
The operating frequencies are: 22.05 kHz, 44.1 kHz, 50 kHz with an iteration of 225. The voltage at the transmitter is 10 V and at the receiver is 3 V. Transducers active diameter is 12.35 mm. The samples under investigation are beads from glass and steel of 4 mm and 6.36 mm diameter.

4. Results discussions

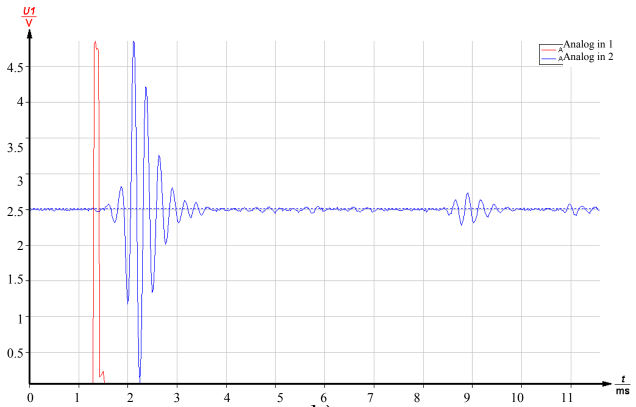
The experiment was made using two systems of beads having at the emission the frequencies of 22.05 kHz, 44.1 kHz and 50 kHz at the constant distance of 70 mm between the sample and transducers. There are recorded ultrasonic waveforms in the time domain, the times of growth (tc) and of diminution (td) of RF impulses, the ratio of the times t_1 and t_2 corresponding to the first two RF signal cycles (TPR) [7] as beeing the ratio of two succesive peak amplitudes in the time domain, the peak frequency f_p, the bandwidth and its relative variation in the frequency domain.

a) The system consisting of 30 glass beads of 4 mm diameter:

The ultrasonic waveforms for the three frequencies and the ultrasonic spectrum where the first impulse is given by the transmitter and the second one by the receiver are shown in Fig. 5(a,b,c)



a)



b)

Fig. 5 a) The ultrasonic waveform at 22.05 kHz frequency b) The ultrasonic waveform at 44.1 kHz frequency.

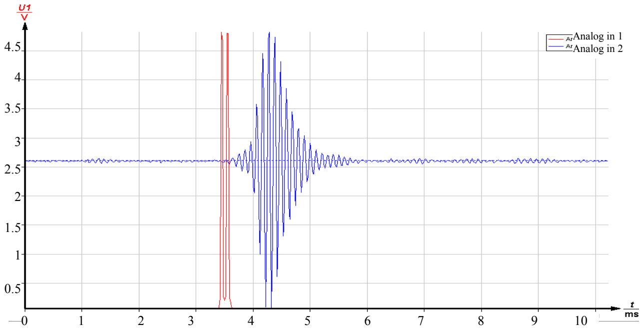
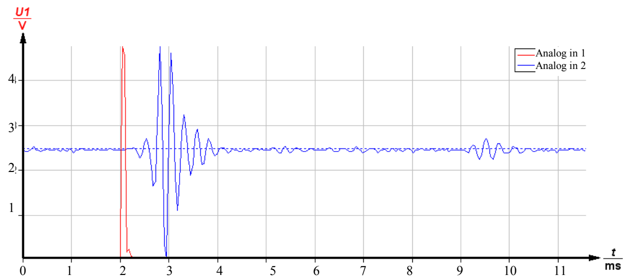


Fig. 5 c. The ultrasonic waveform at 50 kHz frequency.

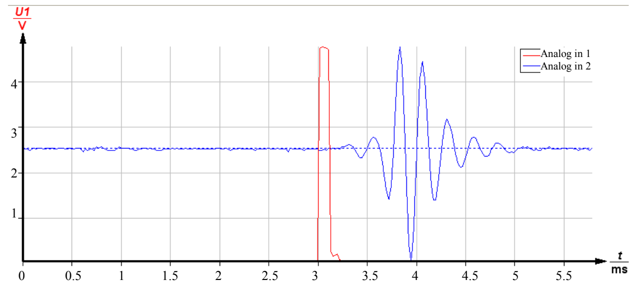
Analyzing the three waveforms one notices that the received impulse duration decreases with the increase of the transmitter frequency, the curve shape is changing and secondary impulses appear at low frequencies and disappear when the frequency increases.

b) The system consisting of 11 steel beads of 6.36 mm diameter

The ultrasonic waveforms for the three frequencies and the ultrasonic spectrum where the first impulse is given by the transmitter and the second one by the receiver are shown in Fig. 6 a,b,c.



a)



b)

Fig. 6 a) The ultrasonic waveform at 22.05 kHz frequency b) The ultrasonic waveform at 44.1kHZ frequency.

A strict anal ysis of the waveform for the system consisting of steel beads shows a different aspect comparative to the case of the glass beads: the impulse duration is bigger, the number of cycles is bigger and the waveform is lighter; these characteristics correspond to the arranging system of the steel beads in a monotone chain. A comparative study shows that even the attenuation is slower for the steel beads.

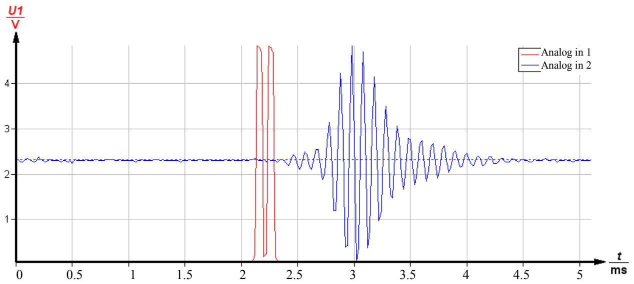
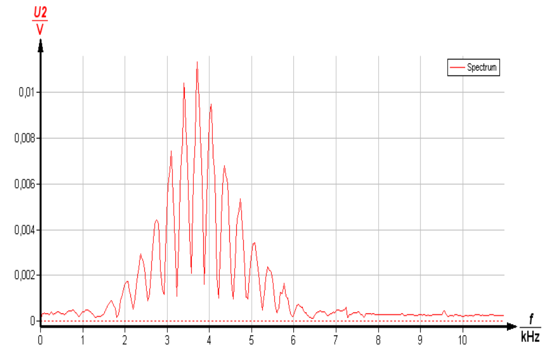
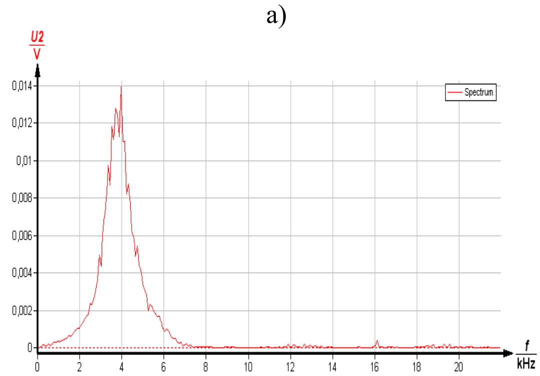


Fig. 6c. The ultrasonic waveform at 50KHz frequency.

The frequency spectrum for the system of glass balls is shown in Figure 7 (a,b,c). One notice that at the transmitter frequency of 22.05 KHz, the spectra shows five secondary lobes on each part of the frequency peak, at the receiver. These secondary lobes are more diminished when the transmitter frequency increases and disappear completely at the frequency of 50 KHz.



a)



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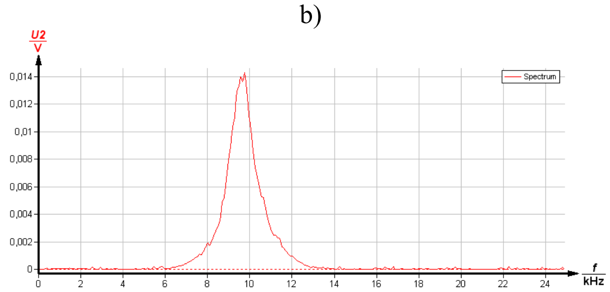
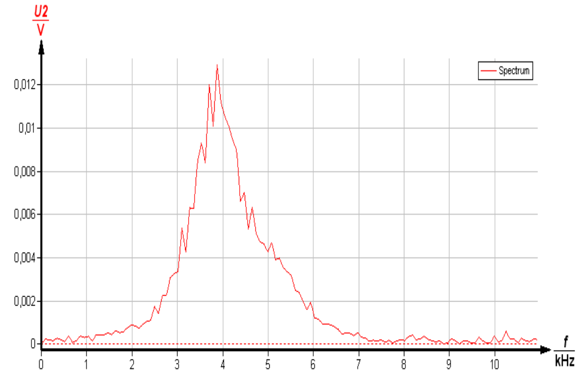


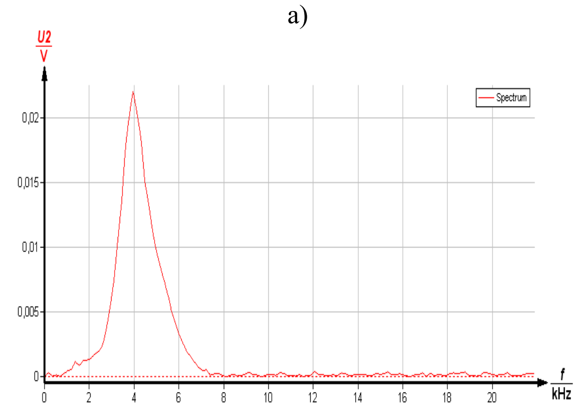
c)

Fig. 7 a) Frequency spectrum for glass at 22.05 kHz frequency b) Frequency spectrum for glass at 44.1 kHz frequency c) Frequency spectrum for glass at 50 kHz Frequency.

For the system of steel beads one can notice from Figure 8 (a,b,c), the same shape of the frequency spectrum but without significant secondary lobes and a more pronounced flattening at low transmitting frequencies.



a)



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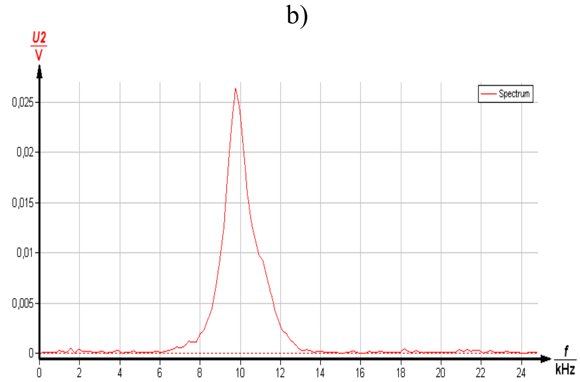

c)

Fig. 8 a) Frequency spectrum for steel at 22.05 kHz frequency b) Frequency spectrum for steel at 44.1 kHz frequency c) Frequency spectrum for steel at 50 kHz frequency.

Table 1

Samples	Frequency (kHz)	Δt (ms)	TPR	Δf/fp
Glass	22.05	1.089	0.900	38.8
	44.1	1.043	0.894	29.6
	50	1.040	0.977	6
steel	22.05	1.270	0.925	29.4
	44.1	1.020	0.944	37.6
	50	1.360	0.967	14

The appearing of secondary lobes in the received frequency spectrum, more pronounced for the glass beads system, might be due to the number of beads (30) and to their balling system by gravitational depositing. In this case, at low transmission frequencies, the depositing geometry at the equilibrium being of a "cluster", there is the possibility that the frequency response to be strongly scattered and dissipated, this aspect being also noticed at the accentuated attenuation of the waveform (see Fig. 5a). The confirmation of this possibility is also given by the value of the acoustical parameter TPR (0.900 and 0.925, respectively) at low transmission frequencies.

Because the experimental device presents an inner diameter bigger then the beads diameter, by applying the dropping gravitational method, the glass beads are arranged in a 3 superposed beads system at the equilibrium. In this case, the ultrasonic response of the incident wave is composed of many reflections from the device's walls and from each glass bead of the system. At low frequencies (22.05 kHz), these reflections are numerous being well visualized by the appearing of many lobes of secondary frequencies in the aspect of the frequency spectrum; but the increase of the transmitter frequency leads to their disappearing (see Figure 7a). In the case of the steel beads, where there are arranged in a vertical beads chain, the ultrasonic response of the incident wave is given more clearly by the reflections from the device's walls and from each steel bead. Therefore, the aspect of the frequency spectrum doesn't contain lobes (see Fig. 8a) and when the frequency increases, the spectrum presents an approximate ideal aspect (see Fig. 8c).

5. Conclusions

The analysis of the Table 1 shows that the impulse duration is almost constant for the glass beads and is increasing for the steel ones. Thus, one consider that the information obtained by the ultrasonic response at the transmitter is composed of multiple reflections and scatterings of the incident acoustical wave. This offers a mechanism for understanding the acoustical wave propagation in granular media and that could be used for analyzing weak perturbations. The combination of energy diffusion with energy loss in the inelastic contacts between grains lead to a net energy dissipation of a coherent wave detected by the receiver. After the first reflection, the acoustical wave becomes so weak and scattered that it cannot be measured as a coherent entity. Because other reflections cannot be noticed up to high frequencies, it is possible that pressure oscillations not to be the result of the reflection from the device walls but of the vibration of the forces chains.

The simulations made by various researchers using the method of discrete elements, lead to results that are identical with the experimental ones. The program follows a specific number of discrete elements (grains) by integrating the motion equation so in any minute, the state of each grain is known. The duration is equal to a tenth of the smallest value of the grain oscillation period at a contact time of type Hertzian. The model is quasi-static having imposed the following conditions by Nesterenko [9]: the forces from the material must be smaller then the elastic limit; the contact surface must be smaller than the grain surface; the typical collision duration must be bigger then the oscillation period of the distorted grain.

Thus, in the case of the glass beads, the ultrasonic waveform and the frequency spectrum visualized at the low frequencies can identify multiple reflections and an accentuated attenuation comparative to the steel beads system.

Granular materials that show complex geometry need a high level of analysis in order to detect and characterize their behavior at different exterior actions. The extension to which nondestructive examination with ultrasounds can be used currently, could be enhanced by a detailed analysis of the information contained in the reflected and transmitted waveforms.

References

[1] P. G. de Gennes, Europhys. Lett. **35**, 145 (1996).
[2] C. Coste and B. Gilles, Eur. Phys. J. B **7**, 155 (1999).
[3] W. A. Grandia, S. M. Fortunko: NDE 1995 IEEE International Ultrasonic Symposium Seattle, Washington, Conf. Proc., 697 (1995).
[4] Katalin Bagi, Granular Matter **7**, 31 (2005).
[5] M.de Billy, J. Acoust. Soc. Am. **108**(4), 1486 (2000).
[6] R. Zagan, P. Petculescu, 6th International Balkan Workshop on Applied Physics, 2007.
[7] A. Kumar, T. Jayakumar, R. Baldev, Philosophical Magazine A, **80**(11), 2469 (2000).
[9] V. F. Nesterenko, J. Appl. Mech. Techn. Phys. (USSR), issue 5, 733 (1983).

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