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Ultrasound propagation in wet and airless non-consolidated granular materials

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ABSTRACT

This paper deals with an experimental description of the acoustic behaviour of non-consolidated granular materials submitted to static force. The aim of this work is to investigate the effect of a small amount of an interstitial fluid on the acoustic propagation. Measurements of the velocity and of the transmission of the coherent wave are performed for different values of the applied force. It is shown that the behaviour of the speed of the ultrasonic coherent wave according to pressure have a slope close to the one of the Hertz–Mindlin's model in the case of a dry medium. When a small amount of a low viscosity fluid is added in a mono-disperse granular medium, the speed of the ultrasonic wave increases according to the power 1/6 to the force applied following the Hertz–Mindlin law ($v \sim P^{1/6}$). Moreover, measurements of the velocity and of the transmission of the ultrasonic wave are strongly dependent on the nature of the interstitial fluid. In order to quantify its effect on the propagation, measurements are performed using various fluids having different characteristics. In a first step, silicon oils of different viscosities (from 50×10^{-3} to 10 Pa s) are used, showing that with increasing viscosity, the wave velocity no longer varies according to the power law 1/6. The transmission coefficient also increases with the viscosity, showing a better propagation of the wave through the medium. Then, measurements are done in the vacuum allowing a comparison with ultrasonic propagation in presence of an interstitial fluid. This experiment shows a strong increase of the transmission coefficient while velocity remains the same as in the dry case. The study of scattered waves in vacuum shows also a significant increase in amplitude and duration of these typical waves. Then, different saturating inert gases are added to the medium showing that the propagation of the scattered wave is not influenced by their different characteristics.

1. Introduction

Dry granular media are composed of grains which interact mainly through two kinds of forces, elastic repulsion, and friction. In such a medium, photo-elastic visualizations experiments and simulations show that the contact forces between grains are strongly inhomogeneous, forming a network of force chain carrying most of the force in the system. When a static pressure is applied to the system, the sound velocity presents a dependence on the power 1/6 to the force applied as expected by the Hertz–Mindlin law. This phenomenon has been experimentally verified for a single chain of beads of identical diameter [1] and for a 3D system composed of beads of diameters included in the range [400−800 μm] [2]. When a small amount of fluid is added to the medium, a thin fluid film around each particle appears and adds at least two more forces to the problem, an attractive force due to the creation of a meniscus between two beads and a viscoelastic force at the wet contact. This meniscus gives rises to unexpected phenomena depending on the nature of the fluid. In this work, the volume of fluid added is about 50 mm^3 leading to a volume fraction of fluid equal to 0.6%. This ratio remains the same for all the liquids used. From the work of Halsey [3] and Masson [4], three distinct regimes for the capillary force exerted by a wetting fluid according to the added fluid volume per contact can be observed. For the quantity of liquid used in this work, the fluid is present in asperities formed by the roughness of the surface.

Different works on the influence of a fluid added to a granular medium show the importance of forces occurring due to the presence of the fluid [1,5–7]. For instance, in the case of a granular aggregate, the fluid situated at the contact between two grains leads to an increase of the wave velocity according to pressure [5] by an increase of the number of close contacts. Moreover, the velocity of a wave propagating in such a medium is sensitive to the quantity of liquid present in the material. It increases until the volume of fluid added is equal to 0.2% the volume available between grains, and remains constant after this threshold value. Measurements of the variations of the thermal conductivity k of a granular material according to the quantity of fluid show the same behaviour [8]. Variations of velocity in this work are then not assumed to be due to differences in the quantities of fluid

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added. On the other hand, when the wavelength is of the order of grain size, scattering effects occur. This high frequency wave can be compared to coda waves [6] and its study can lead to a better comprehension of the propagation of such a natural wave. After a short description of the experimental set-up used in this work, measurements of the velocities of both, longitudinal and shear, waves are presented. The corresponding transmission coefficients through a granular medium, depending to the applied pressure, are discussed in the dry and wet cases as well. Finally, a section is devoted to compare the features of the scattered wave obtained at normal ambient conditions to data obtained under vacuum. Measurements for different saturating gases are also performed and compared to the case without air in the medium.

2. Experimental set-up

The experimental set-up, first introduced by Jia [2,6], is a classical configuration to carry out measurements of ultrasound transmission. Two ultrasonic transducers are embedded at the top and at the bottom of a granular material contained in an aluminum cylinder of 50 mm diameter. These two transducers allow an excitation of the medium with a one-cycle pulse centered at $f = 500$ kHz and both compression and shear waves can be excited. The granular medium is composed of a random packing of poly-disperse glass beads having a diameter contained in the range [400—600 μm]. The height of the medium being about $L = 11$ mm, the volume fraction of solid phase obtained is about 0.65. The large difference between the diameter of the cylinder and the height of the medium allows us to avoid horizontal stress chain facing the container walls. At the top of the granular cell, a screw is used to apply a normal force to the medium. The applied pressure ranges from 0.08 to 3 MPa and is measured by a regular strain gauge sensor. Thus, the velocity (v) and the transmission coefficient ($|T|$) of the acoustical wave, deduced from delay and attenuation of the wave during the propagation through the medium, are measured for different values of the applied force. The sound velocity in such a medium varies with the pressure P_0 to the power 1/6 according to the Hertz–Mindlin model. These two values being linked together with a coefficient depending on the elastic characteristics of the material of which are done the beads used (Young modulus and Poisson ratio), and on the physical characteristics of the beads (radius and density). Moreover, the velocity is also dependent on the average coordination number Z and on the compaction Φ of the medium [9] which in turn depends of both, the number of beads and of the height of the medium. An ultrasonic transducer is thus added to the experimental set-up in order to measure the variations of the height of the medium, allowing us to estimate the variation of the compaction during the experiment. To avoid large variations of the compaction for different experimental runs, a succession of load and unload cycles are applied to the material before all measurements, allowing a rearrangement of beads in the medium and a quite good repeatability. Measurements of the wave velocity are then done for an equivalent compaction.

3. Acoustic behaviour in presence of an intersticial fluid

3.1. Longitudinal wave propagation

This section presents the features of a longitudinal wave propagating through a granular medium for an external applied force included in the (0.08—3) MPa range. The signal transmitted is a 500 kHz longitudinal pulse and the receiver is also longitudinal. Elastic and mechanical properties of the inter-grain contact are modified by adding about 50 mm^3 of a viscous fluid which, after mixing, creates a homogeneous fluid film around each bead. At the contact between two grains, the presence of the fluid is supposed to induce a hardening of inter-grains contact with respect to ultrasound propagation. This effect allows an increase of the wave velocity as showed by Job on the propagation of nonlinear solitary waves in a chain of beads [10]. The properties of fluids used in this experiment are presented in Table 1.

Table 1
Properties of fluids used in this experiment.

	Water	Silicone oil	
		47V50	47V10000
Viscosity (Pa s)	1×10^{-3}	50×10^{-3}	10
Density (kg m^{-3})	998	959	973
Surface tension (mN m^{-1})	73	21	21
Bulk modulus (10^8 Pa)	–	8.65	6.73

Fig. 1 presents the evolution of the velocity and of the transmission coefficient of a wave propagating in a granular medium measured according to static pressure, P_0, for the dry case (ambient conditions) and for wet cases, *i.e.* for different fluids added to the medium. Note the different pressure scales used in Fig. 1a and b, which are $P_0^{1/6}$ and P_0 for the velocity and the transmission coefficient respectively. Appears in Fig. 1a the Hertz–Mindlin model which predicts a power law with exponent 1/6 for the sound velocity as a function of the static force applied on the material. The velocity of a simulated wave propagating through a granular medium follows a linear behaviour with the pressure to the power 1/6. In logarithmic scales, when the force is increased, the theoretical velocity is a linear function of the force with a slope equal to 1/6. The experimental dry case presents a slope lower than the model's one (Fig. 1), equal to 0.14, the small difference between both slopes being attributed to the polydispersity of the beads. The coefficient linking velocity to pressure applied of the experimental dry case is then measured lower than the theoretical one.

In order to quantify the effect of a small quantity of fluid on the wave propagation, a small amount of water is firstly added to the granular material taking care to have the same compaction as in the dry case. It appears that while the velocity of the longitudinal wave is lower than the one obtained in the dry case, the transmission coefficient remains nearly unchanged. This non-viscous fluid slows down the propagation of the longitudinal wave, without significant losses of energy. The use of a silicon oils of viscosity $\eta = 50 \times 10^{-3}$ Pa s presents an increase of the velocity of the longitudinal wave in the medium while its slope remains the same as in the dry case. When a fluid having a viscosity $\eta = 10$ Pa s is used, the velocity is increased and remain a linear function of the force but the slope is now about 0.10.

For viscosities up to $\eta = 10$ Pa s, the wave velocity still increases as $P_0^{1/6}$. However, the proportionality factor (corresponding to the slopes in Fig. 1a) is about 37% smaller compared to the low viscosity case. Both silicon oils having a surface tension σ very close, this parameter is not involved in the increase of the velocity. The term σ is thus neither responsible of the velocity increase nor of the decrease of the slope. According to the volume V of fluid added to the system, in the considered regime [3], the cohesive force $f_a = \sigma V / l_r^2$ exerted is proportional to the volume of liquid at a contact and depends on the roughness length scale l_r corresponding to the asperity height. The radius of the spheres does not play any role for such a quantity of fluid added. The weak value of the cohesive force for the medium considered here and the fact that two viscous fluids having the same surface tension value leads to a really different behaviour mean that none of these two parameters, f_a and σ, can explain the hardening of inter-grain contact leading to the increase of the wave velocity. Moreover, the fluid having the highest effect on the propagation of the wave have the weakest bulk modulus. Only the differences of viscosity leads to a significant difference

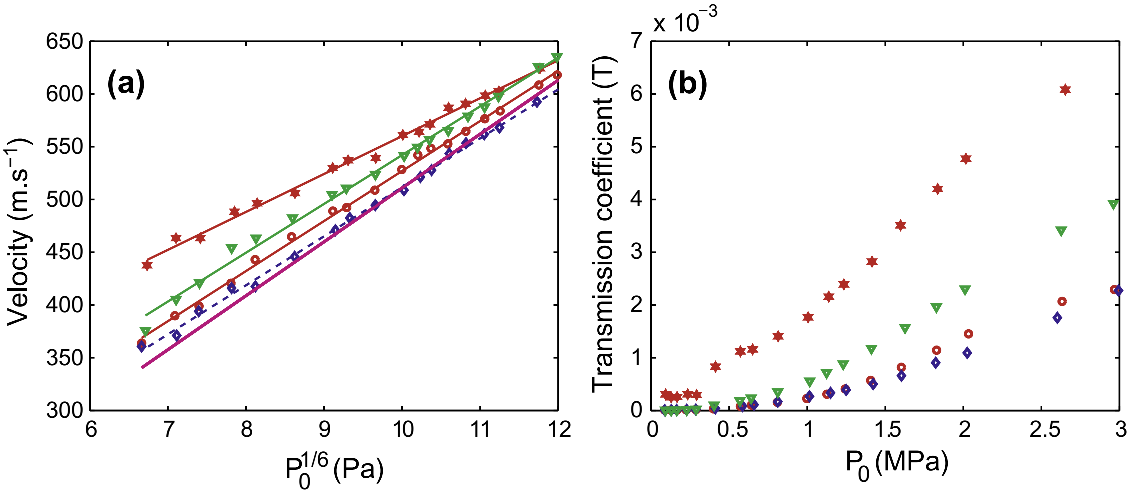

Fig. 1. Evolution of the velocity modeled by the Hertz–Mindlin model (—) and of the measured velocity (a) and transmission coefficient (b) of a longitudinal wave for the dry (–○–) and wet cases (water (- -◇- -) and oil of viscosity 50 × 10^{-3} Pa s (–▽–) and 10 Pa s (–∗–)).

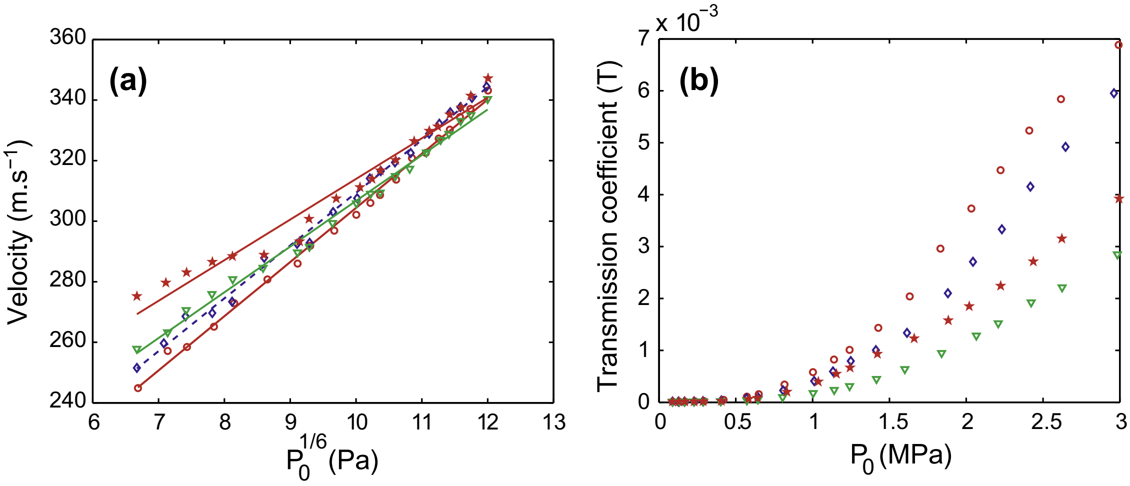

Fig. 2. Evolution of the velocity (a) and transmission coefficient (b) of a shear wave for the dry (–○–) and wet cases (water (- -◇- -) and oil of viscosity 50 × 10^{-3} Pa s (–▽–) and 10 Pa s (–∗–)).

in the velocities and transmission coefficients measured. One of the explanations of the increase of velocity according to the viscosity of the fluid is that the liquid trapped in the meniscus which forms at asperities of the rough surfaces of the beads leads to a hardening of the contact between two beads as was suggested by Job [10], even if in his case, the quantity of fluid added forms macro-meniscus between grains. On the other hand, while the transmission coefficient remains quite the same in the dry and water wet cases, it increases significantly when the added fluid presents a high viscosity, showing thus a better propagation of the wave in the medium. The better bead–bead contact, due to the viscosity of the fluid added, can be involved in the increase of the transmission coefficient, making thus easier the propagation of the acoustical energy of the wave. In order to examine the effect of a small amount of a viscous fluid in the medium on the propagation of a shear wave, the same measurements of the velocity and transmission coefficient according to the force applied on the material are presented in the next section.

3.2. Shear wave propagation

Transducers are now changed in order to measure the acoustical behaviour of the shear wave propagation with an excitation of the medium with a one-cycle pulse centered at $f = 100$ kHz. The transducers used now are both Panametrics V1548. Fig. 2 shows that these waves are slower than the longitudinal ones but the evolution of velocity with pressure does not differ significantly from the behaviour presented by longitudinal waves. The increase of the velocity with viscosity observed in the longitudinal case is also observed for shear waves and when a highly viscous fluid is added, a decrease of the proportionality coefficient of the velocity according to the applied pressure also occurs. On the contrary, the transmission coefficient is high when the medium is dry and decreases in the presence of viscous fluid.

The decrease of transmission coefficient with the viscosity of the fluid shown in Fig. 2b has been highlighted by the works of Brunet [7]. The study of the internal dissipation Q^{-1} (the ratio of energy loss per cycle to peak energy stored) measured from the transmitted intensity of multiply scattered ultrasounds, this kind of wave being dominated by shear waves due to the mode conversion [6], shows an increase of Q^{-1} with increasing static pressure applied. The dominant mechanism in the contribution to the observed dissipation in such a medium is the linear viscous dissipation due to the adsorbed liquid films sheared at the contact area. As previous studies are done in ambient conditions, the ambient humidity, which was about 25% during the experiment, can also affect measurements. Its presence at the contact surface between two spheres can lead to dissipation. In order to identify the effect of the ambient humidity on the acoustic behaviour, measurements of the high-frequency scattered waves are achieved in vacuum in the next section.

4. Acoustic behaviour of the scattered wave in vacuum

The same experimental set-up as previously is used but a air-tight plastic envelops the experimental set-up and a vacuum pump is used to extract the air from the medium. The receiver used in this part (Panametrics V156-RM) allows us to measure the shear waves propagation and has a diameter of 6 mm, which is sufficiently small for the observation of scattered waves. The transmitted ultrasonic signal measured through the granular medium for a 1 MPa compressional force is presented in Fig. 3. A relatively low frequency signal noted A can be seen in Fig. 3 corresponding to the coherent shear wave stemming from the conversion of the longitudinal mode in a shear mode. A high frequency signal, noted B, corresponding to the measured scattered signal [6,2] also appears in Fig. 3. Focusing on the wave A, experimental results show that both velocities, with and without air, remain unchanged, while the transmission coefficient increases significantly as the air pressure decrease.

Moreover, Fig. 4 a and b present the transmitted high-frequency scattered wave measured with and without air. Removing the air from the medium allows a better propagation of the signal B. Its amplitude and its duration time are larger than in the case with air. In the case in vacuum, the humidity is removed from the granular medium. The linear viscous dissipation due to the adsorbed liquid films sheared at the contact area does not occur as there is no humidity thin layer around the spheres and the contact between two spheres is dry. Indeed, removing air from the experiment allows us to remove the humidity from the medium, the system is then considered as dry in the vacuum case.

Jia [6] and Brunet [7] have shown that in a wet bead packing, a drastic effect on the wave amplitude is observed with high-frequency scattered waves in comparison to the dry case. The transmitted intensity averaged over 55 independent configurations of the scattered wave measured for dry and wet granular media is presented in Fig. 5. The intensity for the granular media without air is also reported. When a fluid is present in the medium, comparing to the dry case, a strong dissipation of the high-frequency scattered waves can be observed as was first observed by Jia [6]. On the other hand, the same experiment in vacuum presents an important increase of the scattered wave (Figs. 4 and 5) in amplitude and in time compared to the case in air.

Assuming that the incident sound is a δ function in time and position, it begins to diffuse after traveling a distance z_0 into the

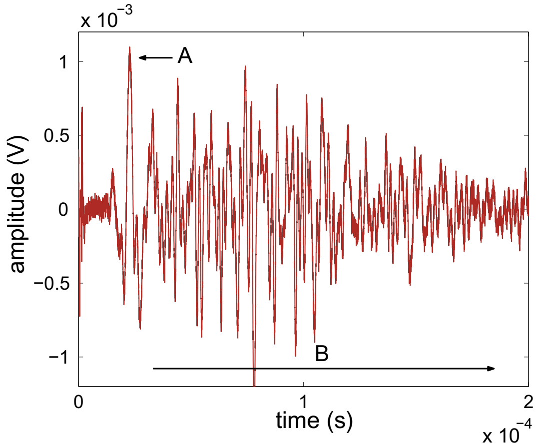

Fig. 3. Enlargement of the transmitted ultrasonic signal through a dry granular material.

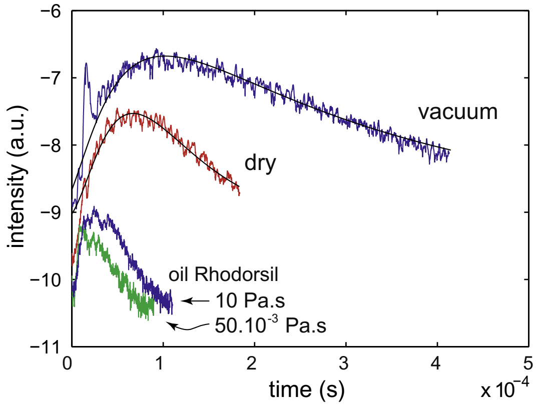

Fig. 5. Comparison of the averaged intensity of the scattered waves traveling across a wet, a dry and an airless granular packing for a 1 MPa applied force. The solid lines (in the dry and airless cases) correspond to the simulated intensities.

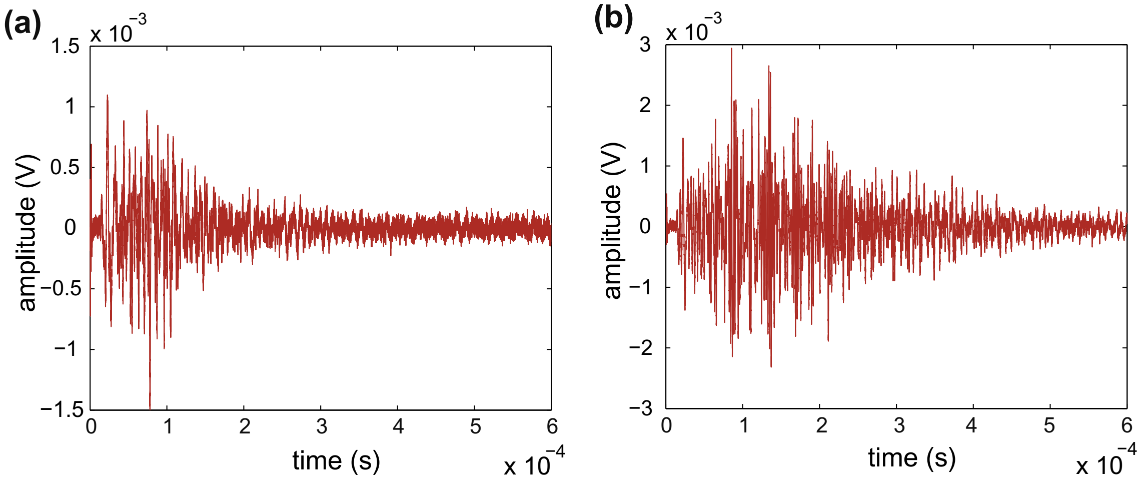

Fig. 4. Transmitted ultrasonic signal through a dry granular material with (a) and without air (b) for a 1 MPa applied force.

sample, and assuming that no diffusing flux is incident into the sample at the faces apart from a contribution due to internal reflections [11,12], Page has expressed the diffusion equation depending on the reflection coefficient $R(\theta)$ of the cell walls averaged over the incident angle θ [13]. When R is very close to 1, it can be assumed that the cell walls are perfectly reflecting at $z = 0$ and $z = L$, and the diffusion equation take the form [6]:

$$J(t) = \frac{v_e U_0}{2L} e^{-t/\tau_a} \sum_{n=0}^{\infty} \frac{(-1)^n}{\delta_n} \cos\left(\frac{n\pi z_0}{L}\right) e^{-D(n\pi)^2 t/L^2}, \qquad (1)$$

with v_e the velocity of the coherent wave, U_0 the energy of the transmitted wave, $\tau_a = Q/2\pi f$ the inelastic absorption time and $\delta_n = 2$ for $n = 0$, otherwise $\delta_n = 1$. Assuming that z_0 can be assimilated to the transport mean free path l^*, the diffusion coefficient D is expressed according to l^* as:

$$D = \frac{1}{3} v_e l^*. \qquad (2)$$

The measured intensity of the scattered waves can be modeled using Eq. (1) as presented in Fig. 5. The solid lines correspond to calculated intensities for different interstitial fluids and are in a good agreement with experimental data. From the diffusion equation, the diffusion coefficient D and the quality factor Q can be obtained by fitting the time profile of the average transmitted intensity. For dry conditions, the best fit is obtained with a set of parameters $D = 0.13\ \mathrm{m}^2\ \mathrm{s}^{-1}$ and $Q = 200$. These values are close to those obtained by Jia [6], in the dry case, for granular samples of three different thicknesses. The fit to the experimental data in the granular packing without air yields $D_{vacuum} = 0.23\ \mathrm{m}^2\ \mathrm{s}^{-1}$ and $Q_{vacuum} = 900$.

The important difference of the amplitudes of scattered waves between the dry and airless cases shown in Figs. 4 and 5 can be due to the ambient humidity which was about 25% during the experiment in ambient conditions.

The same experimental observations of large duration of the scattering waves have been done by Latham [14] in the 1970s about the propagation of shear waves in the outer regions of the moon with measurements of wave trains received from the impact of the Apollo 11 lunar module. It appears an unexpected long duration of the observed signals due to an extremely low attenuation of the moon surface. The assumption is that the moon has a high $Q (Q_{moon} = 3600)$ but also is very heterogeneous. The highly heterogeneity of the media would tend to increase the duration of the seismic scattered waves. In the experiment presented in this work, the term Q is 4.5 times higher in the airless case than in ambient conditions, meaning a higher heterogeneity of the granular medium. Furthermore, the transport mean free path is two times higher, meaning that the scattering phenomenon occurs for a larger distance of propagation of the wave when no air nor humidity is present in the medium. The humidity present in the saturating gas tends to increase the homogeneity of the medium considered. In order to verify the effects on the behaviour of the wave propagation depending on the saturating gas characteristics without considering the humidity, different measurements are carried out using different dry gases. The case named dry case in previous sections is now named ambient conditions case.

Table 2
Properties of saturating fluids used to study the behaviour of the scattered wave.

	Dry air	Argon	Neon
Viscosity (μPa s)	18.6	22.9	32.1
Density $(\mathrm{kg\ m^{-3}})$	1.25	1.78	0.9

5. Behaviour of scattered waves for different saturating gases

Fig. 5 shows that the presence of a saturating gas has a strong effect on the propagation of the scattered wave in the granular medium. With the lake of humidity around beads during the experiment in vacuum, the diffusion coefficient and the quality factor of the scattered wave are higher than in ambient conditions. In order to check which properties of a saturating gas could affect the propagation of such a wave, measurements are done using different inert gases and are compared to measurements in dry air. Hygrometry is thus not considered for these experimentations. Table 2 presents the characteristics of gases used.

A first measurement is done with dry air and compared to measurements presented in previous section. Fig. 6a presents the intensities of the scattered waves measured in the ambient conditions, in the vacuum and with dry air for a 1 Atm static pressure.

It appears in Fig. 6a that the scattered waves in the dry air are much more important than in the case of ambient conditions. Comparing the temporal envelops of the scattered waves in the dry air case with the ambient conditions'one and the airless'one, it appears that the difference of duration between the dry air case with the ambient conditions'one is much more important than the difference with the airless one. Although the wave measured in dry air has a temporally decrease quicker than in vacuum leading to a weakest quality factor $(Q_{da} = 600)$, the diffusion coefficient remaining quite equal $(D = 0.22\ \mathrm{m}^2\ \mathrm{s}^{-1})$, the ratio between both

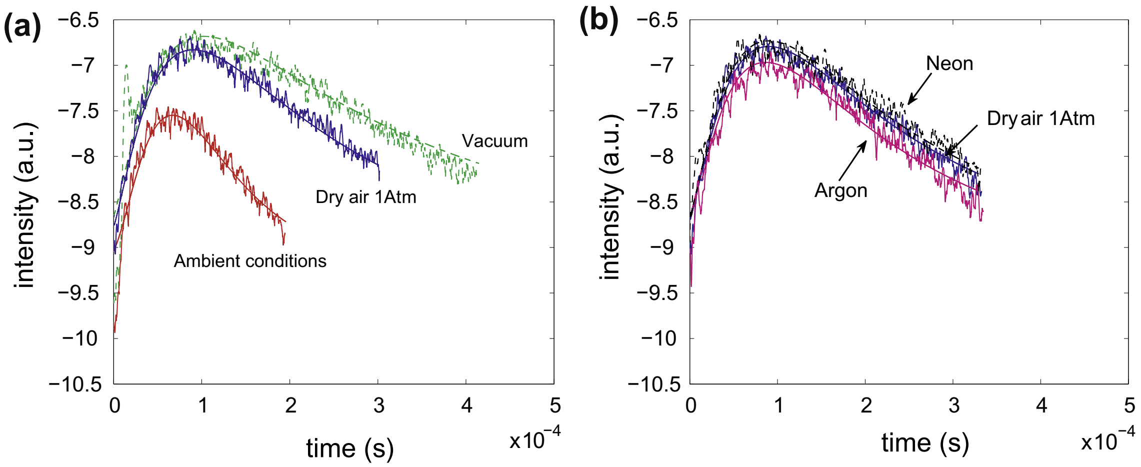

Fig. 6. Comparison of the averaged intensity of the scattered waves propagating in the medium for different conditions of the saturating fluid (in ambient condition, in vacuum and with dry air (a) and with neon, argon and dry air (b)) for a 1 MPa applied force. The solid lines correspond to the simulated intensity.

quality factors (Q_{vacuum}/Q_{da}) is just equal to 1.5. The heterogeneity of the system in these cases can be considered as comparable with such a little difference between their respective quality factor. The diffusion coefficient measured in the dry air case means that scattering needs $l^* = 1.2$ mm to be established which correspond to 2 beads diameters. Furthermore, knowing that in both cases the humidity has been removed from the material, an other characteristic of the system must act on the propagation and be responsible of the temporal quicker decrease of the scattered waves when the saturating gas is dry air.

The intersticial space of the granular material is now filled with inert gases having different viscosity and density, still for a static pressure of 1 Atm. Fig. 6b presents the intensity of the scattered wave measured. It appears that with these gases having a higher viscosity than air, the scattering wave needs also 2 bead's diameters to be established which corresponds to a diffusion coefficient $D = 0.22\ \mathrm{m}^2\ \mathrm{s}^{-1}$. The decrease of the intensity in the large times (from 1×10^{-4} to 3×10^{-4} s) leads to quality factor in the neon and dry air cases equal to $Q = 630$ and $Q = 600$ respectively. Using argon as a saturating fluid, the transport mean free path is quite the same as in other cases. Only the inelastic absorption time is smaller and corresponds to $Q = 560$. The difference of the viscosities of the gases used in this experiment does not affect the behaviour of the scattered wave. However, the density of the gases seems acting on the propagation at a very low level considering that the different quality factors measured for these different gases are quite similar in comparison to the ones measured in the ambient conditions and airless cases. The higher the density is, the smaller the quality factor is, leading to an increase of the internal dissipation Q^{-1}. The fact that the dissipation of the scattered wave is higher with the presence of a saturating gas in the medium and the fact that this dissipation increase with the density of the gas used lead to the assumption that a weak transmission loss of the acoustic energy occurs at the various glass-saturating gas interfaces.

6. Conclusion

With this ultrasonic method for a variable applied force, measurements of transmission coefficient and velocity of ultrasonic waves can be achieved up to 3 MPa. The experiment has been carried out for different conditions of the contact between beads using fluids having different viscosities. The longitudinal wave propagates with a velocity and a transmission increasing with the viscosity of the fluid. On the contrary, in the case of a shear waves propagation, as the velocity increases with viscosity, as in the longitudinal case, the transmission coefficient decreases significantly when a viscous fluid is present in the medium. The same experiment is done in the vacuum in order to avoid the effects of the saturating fluid on the propagation. It appears that the velocity remains the same in the vacuum compared to the case in ambient conditions, but its transmission is higher. Moreover, the propagation of scattered waves in vacuum is increased in time and in space. The study of their intensities and the minimization of the model to data shows that both quality factor and diffusion coefficient are higher in vacuum, meaning that the transport mean free path is increased, *i.e.* the scattering phenomenon occurs for larger distance of propagation of the wave, and the temporal spreading in the latter case is more important than in ambient conditions. The increase of the duration of the observed scattered waves in the airless case is assumed to be due to the ambient humidity in the medium which tend to increase the homogeneity of the system. The study of scattered waves using different saturating inert gases having different properties shows that their viscosities do not act on the propagation of the scattered waves. The study of the time profile of scattered waves averaged intensities in theses cases shows that the higher the density of the gas is, the higher the dissipation is. This characteristic allows us to assume that a little part of the dissipation of the acoustic energy in the medium is due to transmission losses at the various glass–gas interfaces. Which can not be existent in the case of vacuum resulting in a larger temporal spreading. The inelastic absorption time is then higher without air, the transport mean free path remaining quite the same in the case without air and in the case with saturating inert gases.

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