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Identification of Avalanche Precursors by Acoustic Probing in the Bulk of Tilted Granular Layers

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Abstract. Understanding the precursors of granular avalanches is important for the prediction of critical events. As part of the dynamics leading to the avalanche, precursors are identified as collective motions of grains on the free surface. When a granular pile is tilted at a constant angular velocity, precursors appear quasi-periodically. In this paper we simultaneously caracterize precursors on the free surface with an optical method and in the bulk with acoustic methods (nonlinear and linear). Surprisingly, the use on nonlinear acoustic method is not necessary to probe rearrangements in the bulk of the granular material. A linear method can also be used provided that the frequency region is the one where the acoustic propagation is sensitive to the solid skeleton formed by the bead-contact network. Our experiments conducted with monodisperse glass beads show that their surface features are by far the most important for the precursor propreties. Our results allow to probe with a few millisecond time resolution (less than 10^{-2} degree of inclination) the relaxation phenomena associated to each precursor event. Interpretations of different precursors and different experiments provide an interesting train of thought for the understanding of destabilization mechanisms in granular systems.

Keywords: granular media, precursor of avalanche, acoustics
PACS: no. 43.20.-f, 81.05.Rm

A known typical phenomenon occurring in the destabilization of granular media is the avalanche precursor [1, 2, 3, 4, 5]. One of the first experimental laboratory study of avalanche precursors has been carried out by slowly tilting of a three dimensional container filled with glass beads of 2.2 mm in diameter, until avalanche [1]. The surface rearrangements preceding an avalanche were imaged from the top surface of the glass bead packing and processed using a particle tracking method. Large events associated to rearrangements of a significant portion of the surface beads were observed quasi periodically from tilt angles $\sim 15^{\circ}$ to the avalanche angle, and denoted as avalanche precursors. The size distribution function of the rearrangements associated to precursors shows a non Gaussian character and is wider than the one of the small rearrangements Gaussian law. Later, Kiesgen De Richter et al. [3] extended the identification of the precursor regime focusing in particular on the influence of the packing preparation and of the mechanical noise in the measurement system. It has been found that the activity of the free surface is higher for looser packings. Also, the mechanical noise in the system tends to decrease the surface rearrangement activity and the number of precursors. In [2] avalanche precursors were probed in the bulk of the granular layer with a nonlinear acoustic method based on the self demodulation effect. In granular media, nonlinear acoustic effects show a high complexity due to numerous interdependence [6]. One key point of the method is that acoustic waves essentially propagate through the skeleton of the bead packing composed by the beads and their contacts. Correlations between surface and bulk precursors were observed and discussed. However, the observed correlations appeared weak, at least for freshly prepared granular packings and they tend to disappear when the layers are inclined repeatedly forth and back [7]. Recently, the study of Legland et al. [8] opens new possibilities of acoustic probing and it demonstrates that the acoustic propagation is sensitive to the solid skeleton formed by the bead-contact network in a sufficiently low frequency region (a few kHz for gravity loaded mm bead packings). This work demonstrates also the possibility to probe modifications of the bead-contact network with linear acoustic parameters (from the acoustic transfer function of a granular slab).

The present work is a continuation of the in-depth study of the avalanche precursors and their signatures in terms of transient elasticity of the packing. Here we make use of the knowledge on the characteristics of a weakly loaded granular medium acoustic transfer function to target the probing acoustic frequencies and to interpret the measurements [6, 8]. The variations in the acoustic signal transmitted mainly through the bulk of the granular layer are simultaneously compared to surface precursors measured with a camera. Different granular media are tested

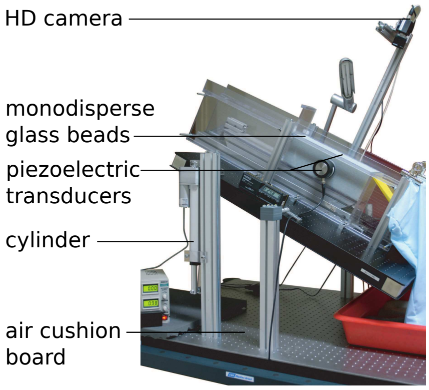

FIGURE 1. Experimental setup: a box of variable size containing grains is slowly tilted until the avalanche. A camera allows to image the free surface of the packing. Piezoelectric transducers are used to probe the bulk with acoustic waves.

to understand better what are the important parameters determining the precursors characteristics. It is shown that cohesion between grains plays an important role in the precursors existence, periodicity and amplitude.

EXPERIMENTAL SETUP

The experimental setup (Fig. 1) is placed on an air-cushion board to isolate the system from external mechanical noise. An electric motor is used to tilt a smaller board on which an open box of variable size is placed. The dimensions of this box are fixed here at 31 cm in length, 10 cm in width and 11 cm in height. The box is tilted at a constant speed in a quasi-static way ($\sim 2.5^{\circ}$/min). A camera mounted above the free surface and rotating with the box registers images of the surface during the tilting process. Two piezoelectric transducers are placed in the middle of the lateral faces of the box and face each other. The granular packing is freshly prepared each time with a protocol which ensures reproducible results. The quasi-monodisperse glass beads (diameters within 1.7-2.1 mm) are poured up to the top of the box. Then, a scraper is passed to remove the excess grains and a grid, initially placed at the bottom, is slowly removed through the beads. Finally the scraper is passed a last time to smoothen the surface. The obtained packing fraction is measured at $\phi = 0.596 \pm 0.010$.

Two sets of beads having different surface natures are used: standard beads, already being used (beads S) and clean beads, washed with ethanol (beads C). The surface properties of the grains are indeed very far leading the characteristics of the avalanche precursors [9]. The cleanest are the grains, the smaller is the precursor periodicity. Measurements are conducted under controlled constant temperature of $22 \pm 1^{\circ}$C and humidity of

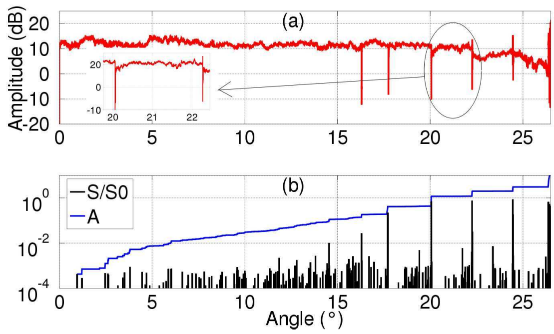

FIGURE 2. **(a)** Level of the demodulated component during a tilt of a packing of S beads. **(b)** Dynamics of surface rearrangements.

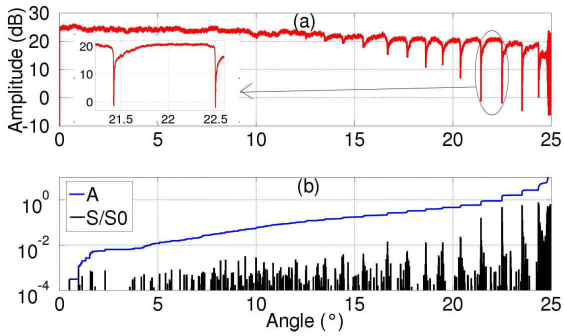

FIGURE 3. **(a)** Level of the demodulated component during a tilt of a packing of C beads. **(b)** Dynamics of surface rearrangements.

$55 \pm 5\%$. Optical and acoustical acquisitions are taken simultaneously. The experimental setup is improved compared to the one used in Kiesgen de Richter et al. [7], mainly because the mechanical noise of the system is much weaker.

Optical Methodology

A step of 0.1 s in time is used between each image, corresponding to an angular interval of $d\theta \approx 3.10^{-3\circ}$. After acquisition, the frames are processed to quantify the rearranged surface portions between two successive frames [3]. It is then possible to plot these rearranged surfaces S, normalized by the total surface S_0, depending on the tilt angle θ. The cumulative fraction of rearranged surface (S/S_0), called activity (1), is also calculated:

$$A(\theta) = \sum_{j=0}^{\lfloor \theta / d\theta \rfloor} \frac{S(j.d\theta)}{S_0}. \qquad (1)$$

An example of such measurement results is shown in Fig. 2(b). The largest events correspond to precursors which occur pseudo-periodically with the tilting angle. The activity increases exponentially until the emergence

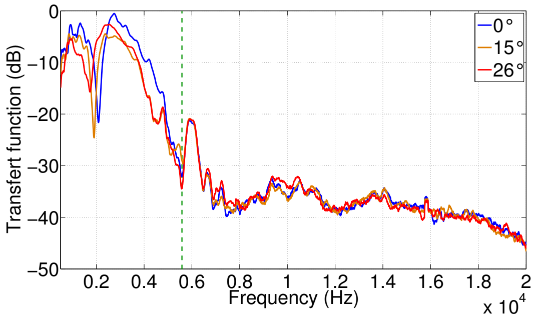

FIGURE 4. Acoustic transfer functions measured during the tilt of the packing of S beads: at the start (0°), at the middle (15°), and at the end, just before the avalanche (26°). The cut off frequency between the two characteristic regimes of propagation is estimated at $\sim$ 5.6 kHz (the green dashed line).

of precursors. The precursors destabilize the pile when their size becomes comparable with the total surface S_0.

Acoustical Methodology

The longitudinal piezoelectric transducers of 4 cm in diameter are in direct contact with the grains. One works as the emitter and the second as the receiver. A modulated signal is excited in order to generate and observe the nonlinear self-demodulated effect. The second harmonic generation and self-action effects are also registered. These nonlinear effects have been observed to be most of the time very sensitive to weak perturbations of the granular packing elasticity [2, 10, 11]. The chosen excited carrier frequency is 11 kHz and the modulation frequency is 1.5 kHz. We reproduce the same experimental configuration as in [2] in order to monitor accurately the precursors. The demodulated component at 1.5 kHz is then monitored to probe grains and forces rearrangements in the bulk of the granular layer.

Also, another acoustic method has been implemented, and consists in generating pulses of 250 μs duration every 100 ms in order to measure the acoustic transfer function between the transducers. The acoustic transfer function of granular media in such configuration exhibits two main propagation regimes [8]. At the lowest frequencies, the detected signals originate from the acoustic waves that propagated though the solid skeleton of the medium. In this frequency domain the signal is then sensitive to modifications of this skeleton elasticity and geometry. At larger frequencies, the received signal mainly originates from the propagation in the air saturating the beads as in an “equivalent fluid”. In this frequency region the received signal is independent of the solid elasticity but only depends slightly on the medium geometry. Consequently, for a better sensitivity to precursors, it is advantageous to work in the lowest frequency regime where the signal is sensitive to the skeleton elasticity. In our case, a sine wave with a 1 kHz frequency is then used. Modifications of the received acoustic signals are analyzed through the level variation as a function of time of the signal received at the excitation frequency.

EXPERIMENTAL RESULTS

The level of the nonlinear (self-demodulated) component at 1.5 kHz is measured during the tilting process until the large avalanche, for both packings of S and C beads (Fig. 2(a) and 3(a)). The surface rearrangements are simultaneously measured and exhibit quasi-periodic precursors and finally an avalanche (Fig. 2(b) and 3(b)). The nonlinear component shows large quasi-periodic fluctuations with a strong level decrease for each precursor. After each precursor the amplitude of the acoustic component relaxes during $0.5^\circ \approx 12$ s until a plateau before to suddenly decrease for the next precursor. The observed results clearly demonstrate the presence of precursors and the correlations with the surface rearrangements are striking. The very low external mechanical noise in the system permits to greatly improve the detection of precursors in the bulk of the medium, possibly associated to contact forces modifications. As expected [9], there are more precursors and they exhibit a smaller periodicity, for the C beads. This observation can be explained if one considers that the cohesion forces are more important for the C beads than for the S beads, assumption which consistent with the larger value of the angle of avalanche obtained for the latter beads. Therefore, for C beads, the medium is less stable when tilted and small rearrangements are more frequent. The larger cohesion between S beads leads to a better stability but also to larger rearrangements (both at the surface and in the bulk) as observed optically and acoustically. The cohesion forces at the micro contacts between beads could come from the formation of capillary bridges, electrostatic or Van der Waals forces.

Acoustic transfer functions are measured for the packing of S beads: at the initial state (0°), at the middle of the tilting (15°), and just before the avalanche (26°) (Fig. 4). It is observed that the lower frequency part of these transfer functions is modified in this tilting process, corresponding to acoustic propagation through the solid skeleton. The cut-off frequency between the solid controlled and the equivalent fluid controlled propagation is estimated at 5.6 kHz. Consequently, when the medium is probed at a 1 kHz sine wave for both packings S (Fig. 5) and C (Fig. 6), a strong sensitivity to the rearrangements is obtained. The signal variability of this linearly propagated wave shows clearly a strong correlation with the surface precursors. In addition to the previously observed

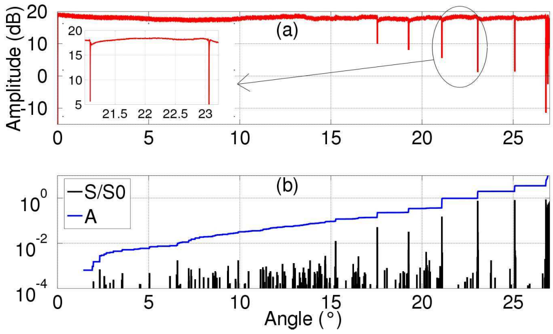

FIGURE 5. **(a)** Level of the 1 kHz linear signal during a tilt of a packing of S beads. **(b)** Dynamics of surface rearrangements.

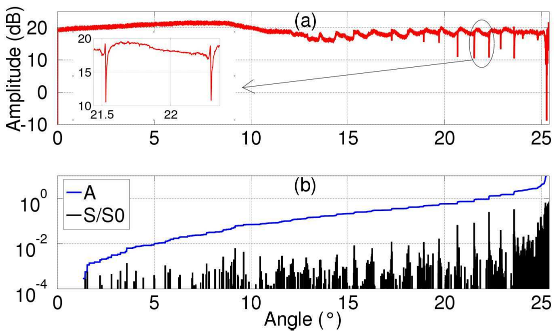

FIGURE 6. **(a)** Level of the 1 kHz linear component during a tilt of a packing of C beads. **(b)** Dynamics of surface rearrangements.

sensitivity of the nonlinear self-demodulated component, we find here that the linear elastic parameters of the packing, probed by the linear acoustic wave at 1 kHz, are also strongly modified during a precursor. The fact that the surface (geometrical) and the bulk (elastic) modifications are strongly correlated indicates that precursors are both of geometrical and elastic natures, and exhibit a certain extension in-depth of the granular layer.

Additional work on the packing elasticity modifications during precursors and the granular layer tilting is currently carried out. In particular, the relaxation of the elastic properties after a precursor is an interesting phenomenon.

CONCLUSIONS

The observation of avalanche precursors when a granular layer is slowly tilted is reported for two different granular samples. These precursors are detected by an optical method monitoring rearrangements of grains at the surface, and by different acoustic methods, probing the linear and nonlinear elasticity of the solid skeleton of the packing bulk (the network formed by the beads and their contacts). We particularly worked on the minimization of the external mechanical noise, in order to obtain clear and reproducible results.

Strong correlations between optical and acoustical detections of precursors are obtained, demonstrating that precursors are both of geometrical nature (at least at the surface) and of elastic nature in the bulk of the layer (at least down to a certain depth). We also show the possibility to probe these events with linear acoustic parameters, measured in a frequency region where the acoustic propagation is sensitive to the elasticity of the granular solid skeleton. Measurement of the acoustic transfer function of the medium allows to estimate this high-sensitivity frequency region.

Avalanche precursors are shown to be different for the two types of bead packings, S or C. This is due to the expected different adhesion forces at the micro-contacts for S and C samples. Interpretations consistent with larger adhesion forces for the dirty beads (S) than for the clean ones (C) are provided. Finally, elasticity relaxation is observed after the precursors and should be studied in details in the future.

This work is supported by ANR 2010-BLAN-0927-01 grant "STABINGRAM" (for STABility loss IN GRAnular Media).

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