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Frequency–amplitude behavior in the incipient movement of grains under vibration

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ABSTRACT

The onset of the movement of particles placed on a horizontal rough surface subject to a vertical sinusoidal vibration is investigated through tracking experiments, theoretical analysis, and numerical simulations. The frequency of vibration needed to move particles decays exponentially with the amplitude of the oscillatory input. This behavior is explained through a simple mechanism in which a forced damped harmonic oscillator with a spring constant represents all the interactions between the particle and the surface. The numerical results compare well with experimental data, demonstrating that the forces included in the numerical calculations suitably account for the main particle response, even though the complexity of the surface is not fully taken into account. Describing the way in which frequency varies with amplitude could be relevant to technological applications such as cleaning of material surfaces.

Introduction

The displacement of grains on surfaces in industrial processes frequently involves an external energy supply from disturbances in, for example, conveyor belts, truck transport, and drilling operations. As a result, the manipulation of granular matter always carries secondary effects, desired or not. Segregation, crushing, jamming, flow fluctuations, particle resuspension and saltation are just some examples. Much scientific attention is dedicated to the solution of the problems related to granular-material behavior, but many questions, especially those related to microscopic interactions between grains and surfaces, have not been answered.

The initiation of displacements of particles deposited on a surface has been shown to be crucial in predicting their possible further resuspension by air flow turbulence (Henry & Minier, 2014; Reeks & Hall, 2001; Valenzuela Aracena et al., 2017). The concept of "fluid threshold" (or the "aerodynamic threshold") was introduced by Bagnold many years ago (Bagnold, 1941; Chepil, 1945; Zingg, 1953). Moreover, the initial destabilization of sand grains by wind is important in resolving whether transport of sandy matter in deserts can be expected (Oger & Valance, 2017).

In the same way, vibration, as a perturbation of a particle's equilibrium, is relevant in many theoretical and applied problems, as, for instance, in the removal of small particles from surfaces in engineering applications (Ziskind, Fichman, & Gutfinger, 2000). Likewise, in manipulation stages of granular matter, the mechanical vibration of grains, either horizontal or vertical, is also an important external perturbation.

Naturally, if the vertical acceleration of vibration overcomes the gravitational acceleration, jumps are observed as typical movements of grains. Studies of the fluidization of granular beds subject to vibrations are common in the literature (Eshuis, van der Weele, van der Meer, Bos, & Lohse, 2007; Renard, Schwager, Pöschel, & Salueña, 2001; Mawatari, Koide, Tatemoto, Uchida, & Noda, 2002), in which the critical intensity required of the external excitations to fluidize grains has been reported. Moreover, even jamming of a drained granular medium was investigated showing its dependence on the time needed for grains to rearrange themselves (D'Anna & Gremaud, 2001). In recent years, the formation of patterns on the surface of vibrated layers of grains has been extensively studied. Depending on the whole set of parameters (such as amplitude and frequency of the excitation, shape and size of grains

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and container) different kinds of standing waves can be observed, with various textures (Melo, Umbanhowar, & Swinney, 1994, 1995; Metcalf, Knight, & Jaeger, 1997). Even basic studies concerning the excitation of small spheres deposited on a horizontal platform has been conducted in the past (Ripperger & Hein, 2005; Tippayawong & Preechawuttipong, 2011).

In describing a system consisting of a particle at rest on a vibrating surface, the first step is to consider a mechanical approach such as that presented in Dybwad (1985). There, the author studies the problem of a particle of mass m deposited on a vibrated surface (quartz resonator) as two coupled springs. The particle is linked to the surface via an elastic force with constant k. The quartz resonator has a mass M with an elastic constant K, and its resonance frequency depends only on its elastic properties. The frequency of the coupled system (particle–quartz resonator) is found to depend on the elastic force constant, k, of the particle. The frequency behavior is found to contradict the mass loading expectation, i.e., that the frequency of an oscillating system decreases when its mass increases. An experimental estimation of the value of the elastic constant shows that the actual area of contact of the two touching solids (particle and surface) is very much less than their geometrical area, i.e., than the area of contact that could be determined through a direct calculation, given that it may be lowered because of surface roughness (Dybwad, 1985).

As a second step in the description of the perturbation of a particle deposited on a surface, several linear and nonlinear oscillation models were introduced and analyzed in Ziskind et al. (2000) to demonstrate whether particle removal is possible for soft and hard particles on smooth and rough surfaces. One conclusion of that paper is that the natural frequency may be reduced by up to two orders of magnitude if the distance between two contacts at which the particle touches the surface is much smaller than the particle radius. Moreover, they emphasize the idea that the particle behavior is as if they were linked to the surface by springs (Dabros, Warszynsky, & van de Ven, 1994; Ziskind et al., 2000).

Experiments using aerosol particles deposited on a vibrating glass surface demonstrate that the wall vibration plays two opposing roles, i.e., to increase the separation force between particles and the wall, and to increase the particle deposition rate because of the active capture of aerosol particles (Theerachaisupakij, Matsusaka, Kataoka, & Masuda, 2002). In the same way, analytical models show that the frequency of the particle–surface interaction is found to significantly influence the removal rate of micro-particles from a vibrating surface (Tippayawong & Preechawuttipong, 2011). Furthermore, the description of re-entrainment requires the analysis of adhesion and capillary forces between particle and surface, the inertia of the particle when accelerated, and its contact interaction with particles resting on the surface, especially if the roughness is of order of the size of the beads deposited on it. For that reason, vibrating surfaces as an indirect means for the measurement of adhesion forces between a particle and a wall were used in Hein, Hucke, Stintz, and Ripperger (2002), by correlating particle re-entrainment events with the acting acceleration.

To conclude, we may say that the dynamics involved in the initiation of a particle movement on a surface subject to an external perturbation is not simple, and the inclusion of all parameters playing a role is not straightforward (Mullins, Michaels, Menon, Locke, & Ranade, 1992), even when only a threshold velocity for the initiation of movement is sought (Soepyan et al., 2016). As a result, the conditions under which the incipient motion of grains subject to vibration occurs remain unresolved, even for particles of millimeter size.

The aim of the present study is to predict the critical conditions for a particle to move when initially at rest on a vibrating surface, and to evaluate the physical parameters involved in this process. To pursue this objective, we performed a series of experiments using where particles (grains) of various sizes (within millimeter range) deposited on surfaces of different roughness values (built with micrometer glass beads) subject to a vibrational disturbance. We also develop a theoretical approach that describes the main aspects of the particle behavior found. The idea is to find the critical frequency–amplitude pairs needed to initiate the movement of the deposited grains for different bead sizes and materials and to demonstrate that the system behaves like a forced damped oscillator with a weak elastic constant (compared with that of the particle's material) given by the force interaction between particle and surface. In this sense, we follow the ideas previously developed in the work of Dybwad (1985) and Ziskind et al. (2000).

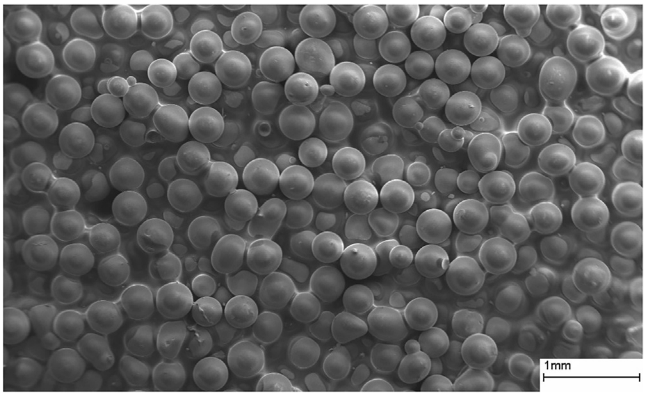

Fig. 1. SEM image of the surface composed of 250-μm-diameter glass beads.

To reinforce our goal, we also perform some numerical tests using a discrete element method with the appropriate interactions between grains and surface, to model the experimental conditions (Herrmann & Luding, 1998). Indeed, we reproduce well the set of experimental results when we included the elastic forces generated by the bead material and also those arising from adhesion and capillary effects.

Experiments

Experimental setup and materials

The apparatus used in the experiments consists of a horizontal rough surface, which vibrates vertically with a sinusoidal motion. Beads are placed on the surface to study the onset of their movement once the vibration begins. The rough surface is fabricated by gluing glass beads onto a flat circular plate of 6 cm in diameter. We worked with two different rough surfaces: one made with 250-μm glass beads and the other made of 500-μm glass beads, with respective size dispersions of 44 and 85 μm. A scanning electron microscope (SEM) image (Fig. 1) was taken to view directly the surface topography created by the 250-μm-diameter glued beads. Because of the way the surface was manufactured, some regions show surface pitting of the second or third layer of beads. This is also observed in the 500-μm-diameter beaded surface.

Regarding the free particles deposited on the surface, we used glass beads with mean diameters of (0.93 ± 0.02), (1.98 ± 0.04), (3.26 ± 0.09), and (3.98 ± 0.03) mm; and stainless-steel bearing balls of 2, 3, and 4 mm.

The plate is fixed to the drive arm of a mechanical oscillator and can vibrate with a selected frequency given by a wave generator connected to it. The plate subsequently induces a vibrational state of the rough surface. The amplitude of the oscillation of this arm is proportional to the signal (measured in volts) of the wave generator. The linear correspondence between voltage and amplitude is verified and calibrated carefully. To this end, we employed two different techniques. The one consists in tracing, with the help of

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