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Aspect ratio of undulation in a vertically vibrated granular layer

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ABSTRACT

The aspect ratio of the height δ to the wavelength λ of the undulation generated by a vertical vibration of the granular layer was investigated experimentally, and its dependence on the frequency f and amplitude a is disclosed. We found that δ/λ is well described by an almost linear function of fa rather than by that of $\Gamma \equiv (2\pi f)^2 a/g$, irrespective of the horizontal size of the container, where g is the acceleration of gravity. Appearance of sub-arches to maintain the main eigenmode and the transitions between eigenmodes of undulation are also elucidated.

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1. Introduction

Vertically vibrated granular layer confined in a vessel shows typical wave motions depending on the amplitude a and frequency f of the external forcing [1–5]. In addition to the planar pattern [6–12] or cross-sectional pattern [13–19] of *ripples*, the cross-sectional structures on the vibrated granular layers, such as the regular pattern of defects [20], transverse bending [21], arches [22], and kinks [23] have been reported. In contrast to the ripples, the latter patterns have common features of wavy deformations characterized by arch-like *undulation* of an almost constant thickness layer with integer or half-integer number of waves along the layer, and alternating ridge-foot positions with a period twice of the forcing period. The onset of the undulation, or the regular pattern of defects, was investigated as early as 1989 by Douady et al. [20]. They proposed a relation between the minimum distance l between "solidified parts" of the layer normalized by the layer thickness h (as shown in Fig. 1) and the non-dimensional acceleration $\Gamma \equiv (2\pi f)^2 a/g$ (f and a are the frequency and amplitude of external oscillation, and g is the acceleration of gravity) described by

$$\frac{h}{l} \approx 0.16(\Gamma - 4.2) \tag{1}$$

We have performed an essentially similar experiment using an experimental apparatus, the details of which have been given in our previous papers [24–26]. A rectangular container made of a transparent acrylic resin with horizontal dimensions $L \times W (W \ll L)$ and height H was mounted vertically on an electromagnetic shaker. The container was oscillated sinusoidally with a frequency f and an amplitude a, so that the position of the container bottom z is given by $z = a\sin(2\pi ft)$. Here

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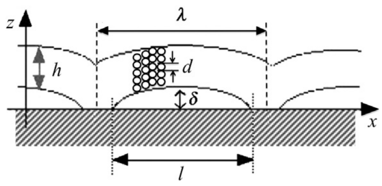

Fig. 1. Definition sketch of undulation.

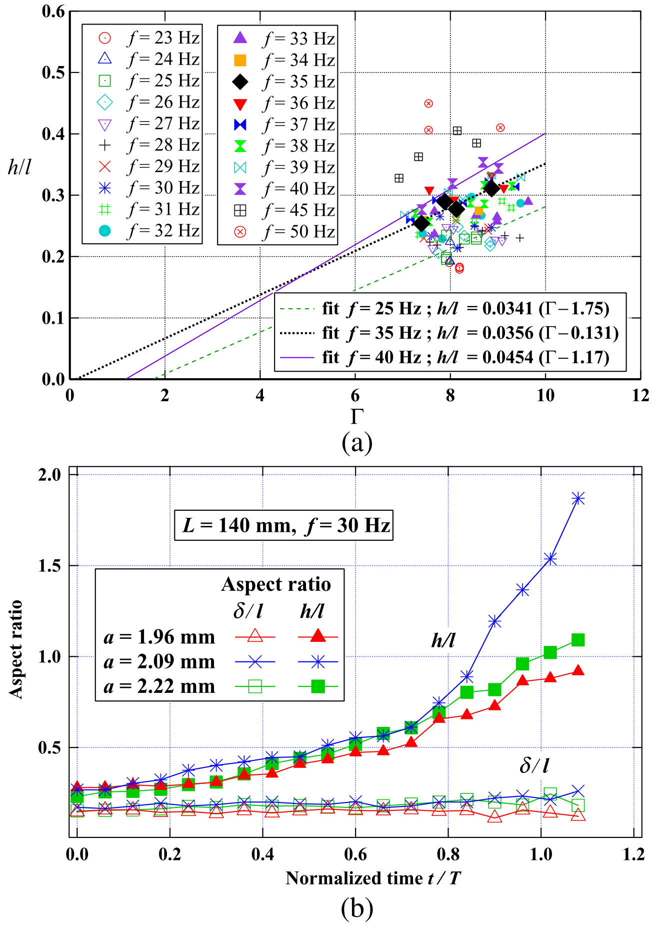

Fig. 2. (a) Dependence of h/l on Γ, and (b) time variation of h/l and δ/l. For the definition of h, l and δ, see the text and Fig. 1. All the data are due to the measurement of the undulation presented in this paper, which may not be appropriately described by a single linear fit in terms of Γ.

we have taken the Cartesian coordinate axes x and z in the horizontal and vertical directions, respectively. The pattern formation of a vertically oscillated layer of granular material of a prescribed thickness h consisting of about ten layers of spherical particles was observed from the side by a high-speed video camera.

We show in Fig. 2(a) the relation of the ratio h/l to the non-dimensional acceleration Γ as was described by Douady et al. [20], where all of the plotted data are the ones obtained in our experiment. In spite of larger scattering, an almost linear relation is recognized for respective frequencies f, which seems to confirm the results of Douady et al. [20]. The slopes and the critical Γ of the fitting curves, however, vary between different sets of external forcing. We also show the time variation of h/l for a particular case in Fig. 2(b). The abscissa is the time normalized by the period of oscillation T, where the time $t = 0$ is chosen when the container's wall is at the lowest position. As has been expected, the horizontal extension l varies with time between 0 and a certain length (of the order of the container size), while the layer thickness is almost constant, so that the ratio h/l varies considerably. This raises a question on the timing of measurement of the arch structure. On the other hand, the ratio δ/l remains almost constant as is shown in Fig. 2(b), where δ is the height of the arch. These results imply that the original Douady plot may not be a universal relation, and/or the characteristic lengths ratio h/l, and Γ may not be appropriate parameters.

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