ACTIVELY ROTATING GRANULAR PARTICLES MANUFACTURED BY RAPID PROTOTYPING

PARTÍCULAS GRANULARES QUE ROTAN ACTIVAMENTE FABRICADAS MEDIANTE PROTOTIPADO RÁPIDO

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We study actively rotating granular particles manufactured by rapid prototyping. Such particles, as introduced in Ref. [1], convert vibrational motion into rotational motion via tilted elastic legs in a circular arrangement at the bottom of the particle. We extend the original design of the particles to make them suitable for mass-fabrication via rapid prototyping. The rotational velocity is measured in dependence of the driving frequency and amplitude. We find two different regimes of motion. For small amplitudes the particle performs a slow and stable rotation, while above a certain threshold the particle starts to perform a precission and consequently rotates significantly faster.

Estudiamos girando activamente partículas granulares fabricados por prototipado rápido . Tales partíıculas , como se introdujo en Ref. [1], convierten el movimiento de vibración en el movimiento de rotación a través de las piernas elásticos inclinados en una disposición circular en la parte inferior de la partícula. Extendemos el diseño original de las partículas para que sean adecuados para la fabricación en serie a través de prototipado rápido. La velocidad de rotación se mide en la dependencia de la frecuencia de excitación y la amplitud. Nos encontramos con dos regímenes diferentes de movimiento. Para las pequeñas amplitudes la partícula realiza una rotación lenta y estable, mientras que por encima de un cierto umbral la partícula comienza a realizar una precision y por consiguiente gira mucho más rápido.

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Particles that perform active motion store and convert energy in internal degrees of freedom to execute a locally directed motion. Examples for such objects are living organisms [2,3], robots [4] and artificial microswimmers [5].

In granular systems some strategies have been suggested to construct such particles. Cylinders [6] and disks [7] with asymmetric mass-distribution have been excited by vertical vibrations to perform a directed motion. Another possibility is to construct particles with asymmetric shape. Chiral S- and U-shaped particles have been shown to convert vibrational into rotational motion [8]. However the interaction of these particles is rather complicated due to their complex shape. In [1] a particle design, called Vibrot, has been suggested, where a ratchet configuration of tilted legs aligned in a circle has been used to achieve a conversion of vibration into rotation. Here the caps of the particles can be almost independently designed from the legs, so that a large variety of particle shapes can be realized. For investigations of the collective behavior of ensembles of such particles, we are faced with the problem to manufacture a sufficient number of particles with small statistical variance.

Here we present an analysis of Vibrot particles manufactured by rapid prototyping. The mean rotational velocity $\overline{\omega}$ of these particles depends on the excitation frequency f_D and amplitude A similar to the original Vibrots from [1]. However, due to the increased stiffness of the legs compared to the original design, we observe two types of motion. For small A we observe a slow rotation and for high A the particles perform a fast rotation overlapped by a precession, therefore, called tumbling regime. The transition from slow to fast rotation is rather sharp, however a transient regime, where tumbling and slow rotation of the particle can both occur is observed in between.

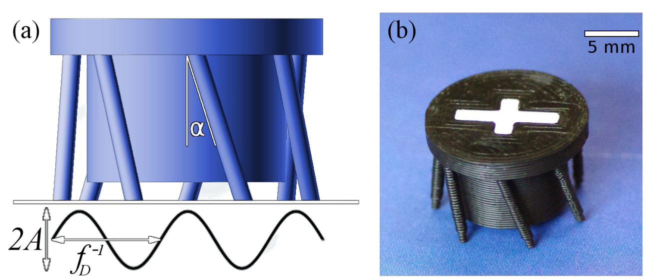

Figura 1. (a) Sketch of the Vibrot. The legs are tilted by $\alpha = 18°$. (b) Photography of a Vibrot manufactured by rapid prototyping. Particles are marked by a cross to simplify tracking of the particle motion.

The original design of the Vibrot contained three elastic legs made of rubber attached to a soft-drink cap. While this assembly is inexpensive and made from household materials such particles are not easily fabricated in large quantities. One possibility to do so, is by rapid prototyping. For this we employed the following changes to the design. The hollow soft-drink cap is replaced by a flat disk with a diameter of 15 mm and a height of 2 mm, to which a cylinder (height 6 *mm*, diameter 11 *mm*) is attached at the bottom, to lower to center-of mass and stabilize the motion. The total number of legs (length 8.5 *mm*, tilt angle $\alpha = 18°$) is increased to seven. This makes the particles more stable against toppling over, when hit from the side. Even numbers of legs are not suitable since in this case the contact points of the legs on a flat surface are symmetric and the particle typically wobbles around the symmetry axis. If the number of legs is too large, legs can join to the central cylinder or break off due to imperfections of the printing process. In systematic tests seven legs appeared to be the optimal number, that increases the stability of the particles, without decreasing the manufacturing throughput significantly.

Particles are printed using a fused filament fabrication (FFF) technique. As printing material acrylonitrile butadiene styrene (ABS) is used. The material has a bulk elastic modulus of 1.5 *GPa*, a density of 1.07 g/cm^3 and a Poisson's ratio of 0.35. Since during the manufacturing the material is deposited in layers, air can be trapped inside small imperfections, which typically reduces the effective density and increases the effective elastic modulus.

To investigate the dynamic properties of a single particle the Vibrot is placed on a polished PMMA (polymethyl methacrylate) plate that is mounted to a electromagnetic shaker and excited by vertical vibrations. Figure 2 shows the mean rotational velocity $\overline{\omega}$ of the Vibrot in dependence of the excitation amplitude A at a driving frequency of $f_D = 50$ *Hz*. No motion is observed for $A < 0.1$ *mm*. For larger A the particles perform a slow rotation where $\overline{\omega}$ increases monotonously with A. For amplitudes $A > 0.16$ *mm*, particles start to perform a fast rotation superimposed by a precession motion, therefore called tumbling regime.

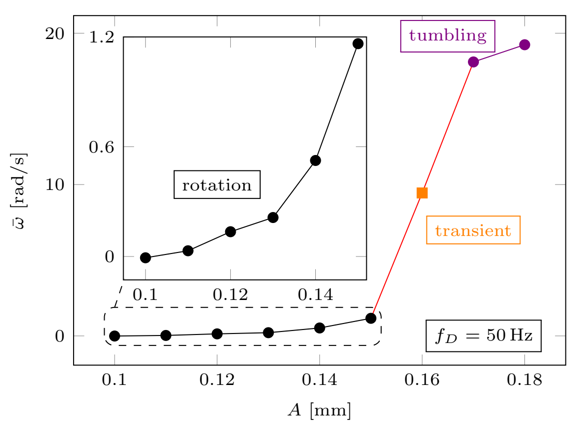

Figura 2. Mean rotational velocity $\overline{\omega}$ of a Vibrot as a function of the excitation amplitude A at a constant frequency $f_D = 50$ *Hz*. Error bars are on the order of the marker size.

Additionally we also measure the instantaneous rotational velocity ω of a particle using a high-speed camera at up to 200 *fps* (see Fig. 3). We find a rather wide distribution, which indicates that ω varies due to the motion mechanism and surface inhomogeneities. In case of the mode of slow rotation, we observe a symmetric distribution around $\overline{\omega}$ while in the tumbling regime the distribution is asymmetric. In the transient mode, we observe coexistence of both types of motion.

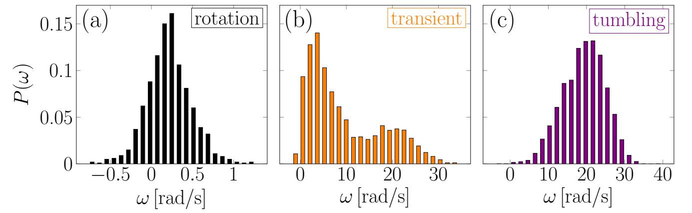

Figura 3. Distribution of instantaneous rotational velocity ω in the regimes of (a) slow, (b) transient and (c) tumbling motion.

Due to the occurrence and transition between different motion regimes the dependence of $\overline{\omega}$ on the frequency is more complex, compared to the dependence on amplitude. Figure 4 shows $\overline{\omega}$ *vs* f_D for two different values of the amplitude. For a low amplitude the particle performs slow rotation where f_D depends non-monotonously on the frequency characterized by a minimum at $f_D = 50$ *Hz*. For large amplitude, we observe slow rotation at low frequency and tumbling motion for $f_D \geq 30$ *Hz*, where the rotational velocity decreases with increasing f_D.

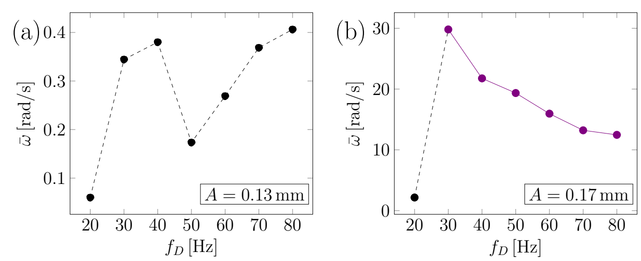

Figura 4. Mean rotational velocity $\overline{\omega}$ of a Vibrot as a function of the excitation frequency f_D for (a) $A = 0.13$ *mm* and (b) $A = 0.17$ *mm*. Error bars are on the order of the marker size.

In summary, we manufactured actively rotating particles using rapid prototyping. The particle design allows the fabrication of particles in large quantities with well-defined rotational velocity, depending on the excitation parameters. The collective motion of such particles reveals a number of exciting effects to be reported elsewhere.

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