Reversal of a granular flow on a vibratory conveyor

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ABSTRACT: Vibratory conveyors are well established in routine industrial production for controlled transport of bulk solids. Because of the complicated interactions between the vibrating trough and the particles both glide and throw movements frequently appear within one oscillation cycle. Apart from the amplitude and frequency, the form of the trajectory of the conveyor's motion also exerts an influence. The goal of our project is a systematic investigation of the dependence of the transport behavior on the three principle oscillation forms: linear, circular and elliptic. For circular oscillations of the shaking trough a non-monotonous dependence of the transport velocity on the normalized acceleration is observed. Two maxima are separated by a regime, where the granular flow is much slower and, in a certain driving range, even reverses its direction.

1 INTRODUCTION

The controlled transport of bulk cargoes by means of vibratory conveyors is of major importance for a whole variety of industrial processes (Rademacher 1994; Sloot & Kruyt 1996). The granular material is usually (i) agitated by a stick-slip drag on a horizontally vibrated deck with asymmetric forward and backward motions, (ii) forced to perform ballistic flights if the vertical component of the acceleration exceeds gravity, or (iii) can be transported horizontally by a vertically oscillating asymmetric sawtooth-shaped profile of the base (Farkas et al. 1999).

Since these phenomena involve the nonlinear interaction of many-particle systems with complex behavior leading to self-organized spatiotemporal patterns, the investigation of vibrating granular materials has become a challenging subject to physicists, too. Such intriguing phenomena as surface waves (Douady et al. 1989; Pak & Behringer 1993; Melo et al. 1994; Metcalf et al. 1997), organized clusters, or segregation effects (Aumaître et al. 2003; Moon et al. 2003) have attracted a lot of attention.

Here we report on a conveyor system with convertible modes of oscillation (Rouijaa et al. 2005) based on the combined forces of four rotating unbalanced masses, which exhibits surprising transport properties caused by *circular* vibrations of the trough (Grochowski et al. 2004).

2 EXPERIMENT

Through the construction of a ring-shaped vibrating channel, the long-time dynamics of a closed, mass conserving system devoid of disturbances from the influx and outpouring of grains can be studied. The main piece of the vibratory conveyor (Fig. 1) is a torus-shaped vibrating channel of light-weight construction (carbon fiber strengthened epoxy) with radius R = 225 mm and a channel width of 50 mm. Firmly connected to the channel are four symmetrically arranged rotating vibrators. The complete oscillation system, the channel and drivers, are suspended with elastic bands in a highly adjustable frame.

By means of four driving units, symmetrically positioned below the trough, the conveyor can vibrate with defined amplitude and oscillation pattern along its entire circumference. This motion can be described by a trajectory performed on a cylindrical surface, consisting of a vertical oscillation $z(t) = A\cos(\omega t)$ superposed with a torsional vibration $\phi(t) = \frac{A}{R}\cos(\omega t + \varphi)$ around the symmetry axis of the apparatus, where φ is the fixed phase shift between the two oscillations. Note that, since the ratio A/R is only about 1 percent, the path of each segment of the tray can be considered to lie almost in a vertical plane. If, for example, the phase shift φ is chosen to be $\pi/2$, then each point on the trough traces a circular path in a vertical plane tangent to the trough at that point.

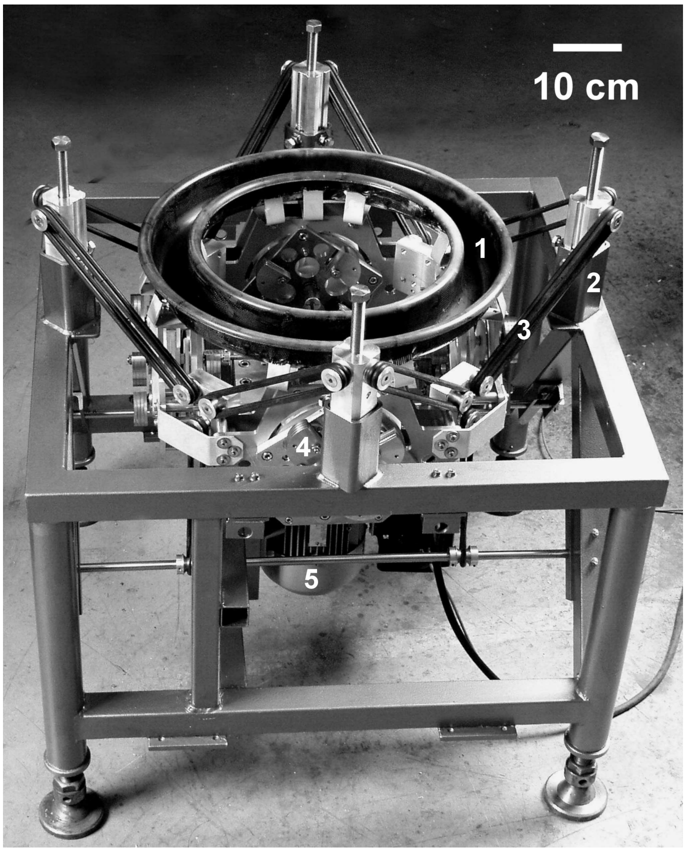

Figure 1. Annular conveyor: (1) Torus-shaped vibration channel, (2) Adjustable support, (3) Elastic band, (4) Vibration module with unbalanced masses, (5) Electric motor with integrated frequency inverter.

For achieving this kind of motion with the inherent possibility to generate different modes of oscillation a special adjustable drive is acquired (Fig. 2a). Unbalanced-mass vibrators are well established in industrial applications since long time. Their working principle is based on a centrifugal force $F = m_\mathrm{u} r_\mathrm{u} (2\pi f)^2$ produced by an unbalanced mass m_u rotating with frequency f, with r_u being the distance between the center of gravity of the unbalanced (eccentric) mass and its rotation axis. A motor driving a load M with one single unbalanced mass will create, for frequencies well above resonance, a circular vibration with an amplitude $A_\infty = r_\mathrm{u} m_\mathrm{u}/M$. A linear motion can be excited by the joint action of two equal vibrators rotating in opposite directions. In consequence, by combining two such linear vibrators oriented perpendicularly to each other, it is possible to generate any desired Lissajous figure by adjusting the phase shift φ between the two oscillations. Three examples of possible modes are shown in Figure 2b.

Each driving unit is built as the above described system of four unbalanced masses, which are placed vertically on both sides of the unit. The oscillation amplitude can be adjusted in steps by changing the number of impaled unbalanced masses.

The four driving units are coupled to the motor via a common central gear box, which keeps all drives in the same phase. The driving torque is transmitted from the gear box to the vibrators by use of rotating rods connected with compensation clutches. The conveyor is driven by an electric motor (Siemens Combimaster 1UA7, with integrated frequency inverter).

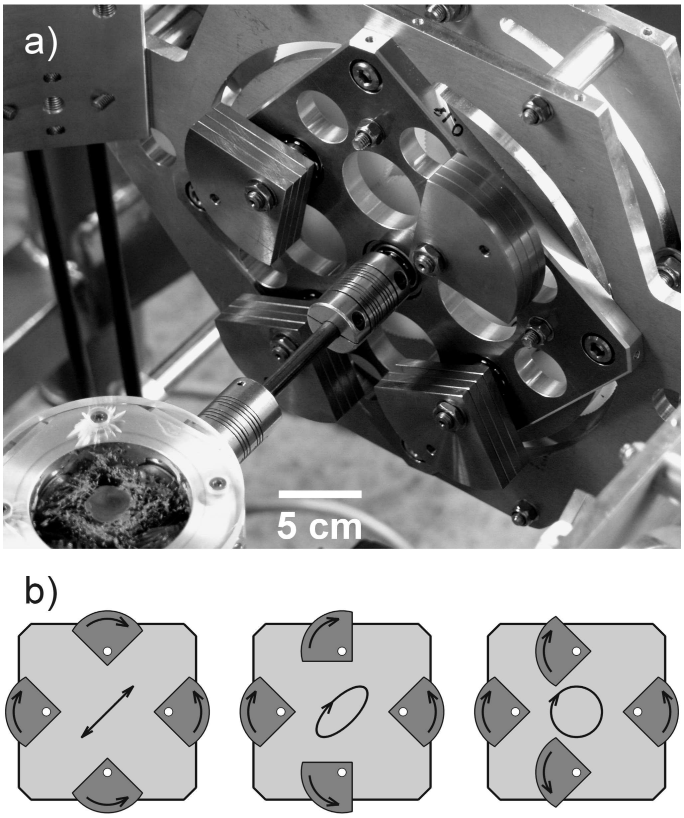

Figure 2. a) Driving module with four unbalanced masses, b) Principle modes of oscillation: linear, elliptic, and circular.

Characteristic of the unbalanced-mass agitated system is the frequency dependence of the vibration amplitude:

$$A(f) = A_\infty \frac{f^2}{\sqrt{(f_0^2 - f^2)^2 + (2\zeta f_0 f)^2}} \qquad (1)$$

The resonance frequency $f_0 = \frac{1}{2\pi}\sqrt{\frac{k_\mathrm{eff}}{M_\mathrm{tot}}} \approx 4.0$ Hz can be limited to a small value (through appropriate choice of spring constant k_eff), so that above resonance, i.e. in the range $f > 3f_0$, an almost constant terminal amplitude $A_\infty = r_\mathrm{u}\frac{m_\mathrm{u,tot}}{M_\mathrm{tot}}$ arises which can be adjusted for fixed eccentricity r_u by the out of balance mass m_u. The frequency response $A(f)$ was measured experimentally before each run. From the measured data, the damping constant ζ can be determined to be 0.08 ± 0.01. The dimensionless acceleration of the conveyor $\Gamma = A(f) \cdot (2\pi f)^2/g$, where g is the gravitational acceleration, can be varied in the range $0 < \Gamma < 7$ by changing the rotation frequency f of the unbalanced masses.

3 RESULTS AND DISCUSSION

For the first trial, the channel was loaded with 450 g of carefully sieved glass beads with mean diameter 1.1 mm. The layer thickness of the grains was about five particle diameters. The average transport speed was determined from the time of circulation of a colored tracer particle that the bulk carried along.

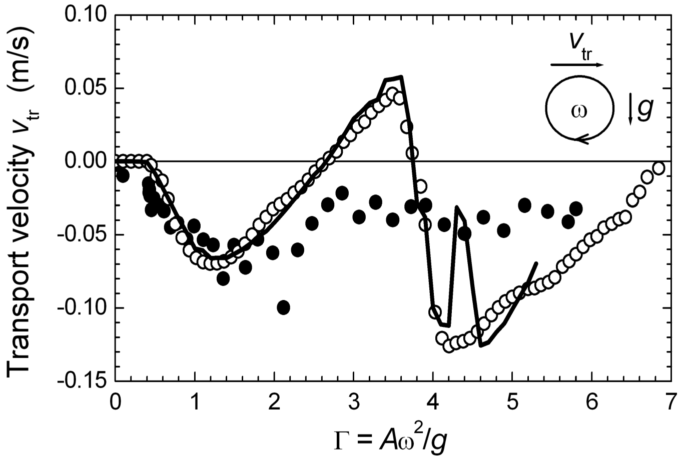

Figure 3. Transport velocity $v_{tr}(\Gamma)$ of a granular flow (≈ 300,000 glass beads with 1.1 mm diameter, ○) on the vibratory conveyor, compared with the mean velocity of one single glass bead (•). Conveyor amplitude $A_\infty = 1.7$ mm. The solid line represents numerical simulations based on an effective block model, see El hor & Linz (2005).

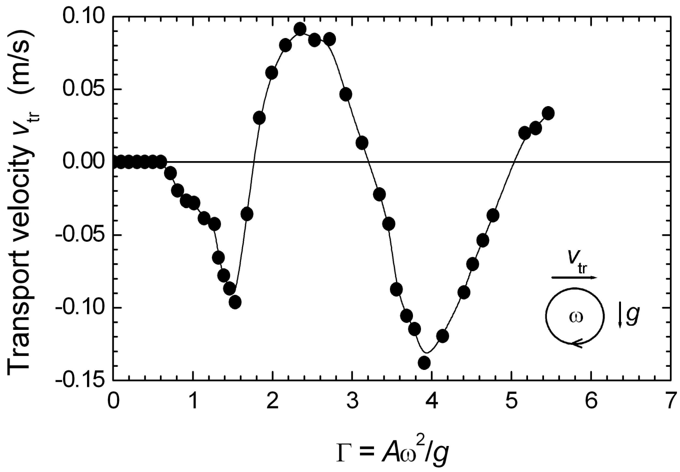

Figure 4. Transport velocity $v_{tr}(\Gamma)$ of an object with low coefficient of restitution (sand-filled 'fingertip'). Conveyor amplitude $A_\infty = 1.7$ mm.

This occurs automatically through a PC supported image processing system that detects the signal changes from the passing of the tracer through a row of the image and records the associated transit time with a temporal resolution of 18 ms. For each Γ we monitor 20 cycles of the tracer particle along the entire circumference of the channel. This procedure allows us to determine the average transport speed within an error of less than 1 %.

The mean transport speed v_{tr} depends, for circular agitation, on Γ in a characteristic manner (Fig. 3). For the case of circular vibrations we define the transport direction of the granulate positive ('forward'), if the rotational direction of the vibration – seen from outside the apparatus – is clockwise while the particles move to the right, or vice versa.

Below a critical value $\Gamma_c \approx 0.45$ the grains stay at rest, i.e., they follow the agitation of the tray without being transported. The onset of particle motion is restrained by frictional forces between grains and the substrate. For accelerations above this threshold the granular material becomes fluidized. Individual particles are unblocked and begin to move freely on top of each other. A net granular flow with constant velocity is observed. Note that this behavior is found already in a regime $\Gamma < 1$ with a vertical acceleration less than gravity. In order to be transported, the granular material does not have to leave the base of the channel. It is sufficient to overcome the frictional forces at the bottom of the granular layer. This transport mechanism due to stick-slip drag on a horizontally vibrated deck with asymmetric forward and backward motions is known as 'sliding'.

If Γ exceeds 1, the vertical component of the circular acceleration will cause the grains to detach from the bulk followed by a flight on a ballistic parabola. The corresponding transport mechanism is called 'throwing'. In our experiments the transport velocity has a first maximum at $\Gamma = 1.2$. A second maximum is observed at $\Gamma = 4.2$. In between, the granular flow is slower and even *reverses* its direction for $2.6 < \Gamma < 3.8$.

In contrast, a single 1 mm glass bead is propagated on this vibratory conveyor in the same direction for all accelerations. The high coefficient of restitution $\varepsilon \approx 0.9$ for collisions between the glass bead and the carbon-fiber tray leads, especially for high Γ-values, to an almost 'random walk' of the particle in the conveyor with a slight tendency to propagate in one direction. This is reflected in the large scatter of the net transport velocity.

In order to study the transport mechanism for a single body in a more controlled fashion ('sandbag test' (Rademacher 1994)) we designed an object with a very low coefficient of restitution and non-spherical shape. The fingertip of a rubber glove was filled with sand. This single object shows qualitatively the same behavior as the granulate (Fig. 4). The regime of velocity reversal is, however, shifted to lower values $(1.8 < \Gamma < 3.2)$.

By varying the unbalanced mass, the amplitude A_∞ of the circular vibration has been changed between 0.53 and 2.35 mm. We find that the transport velocity increases linearly with the amplitude. In order to obtain a dimensionless graph, the granular velocity is scaled by the intrinsic speed of the driving apparatus, i.e. the circular velocity $A\omega$ of the tray. The resulting master curve (Fig. 5) shows clearly that the onset of particle transport depends only on Γ.

The critical Γ values, at which the transport behavior changes qualitatively, are independent of the oscillation amplitude. In the frequency-amplitude parameter space (Fig. 6) the threshold values lie on f^{-2} hyperbola of constant acceleration ('isoepitachs'). However, for $\Gamma > 4$, i.e. beyond the second reversal of flow direction, this scaling behavior is not observed anymore. Depending on the vibration amplitude, the third reversal occurs in the range $5 < \Gamma < 7$ (Rouijaa et al. 2005).

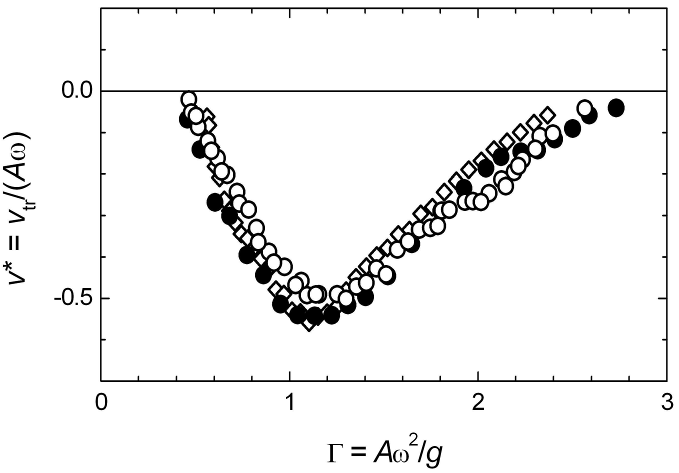

Figure 5. Scaled velocity $v^* = v_{\rm tr}/(A\omega)$ of the granular flow. The experimental data were obtained for three different conveyor amplitudes: $A_\infty = 1.0$ mm (○), $A_\infty = 1.7$ mm (●), and $A_\infty = 2.5$ mm (◇), respectively.

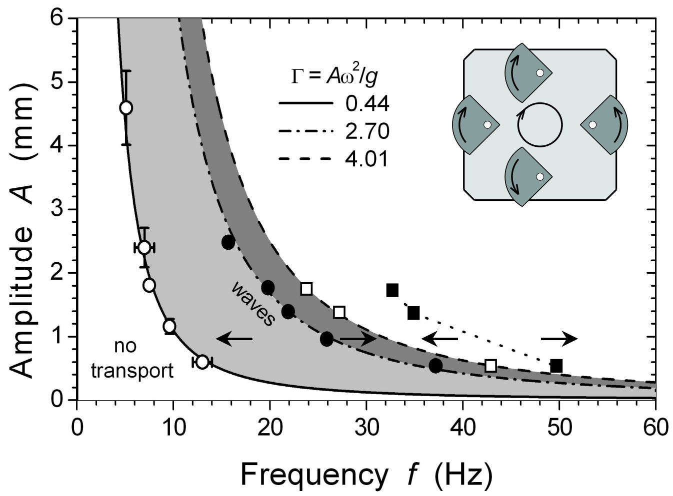

Figure 6. Phase diagram of the transport behavior at clockwise circular forcing. The alternating arrows correspond to the transport direction of the bulk solid.

4 CONCLUSIONS

The vibratory conveyor system introduced here opens up the possibility to investigate the transport properties of granular materials in a systematic way. In principle, with this apparatus all six degrees of freedom of oscillation can be excited individually or in pairs with arbitrary relative phase shift. For the first study, a vertical vibration was superimposed with a rotary oscillation about the vertical symmetry axis of the annular channel and a ninety degree phase difference. This induces a vertical, nearly level circular path for each section of the channel.

Our results show that under certain conditions not even the direction of the granular flow can be predicted a priori. The delicate interactions of the particles with the support as well as among themselves have to be taken into account. First clues indicate that a detailed analysis of the frictional forces becomes important. This suggests that before tackling the full problem of many interacting particles it is even rewarding to investigate the complex behavior of a single object under the influence of a controlled environment (El hor et al. 2005).

For industrial applications, this observed reversal effect is relevant as the direction of a granular flow is selected through the frequency of the excitation alone. One can employ such two-way conveyors for example in larger cascading transport systems as control elements to convey the material to different processes as needed.

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