# First Wavy Instability in Liquid-Fluidized Beds

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## Abstract

The nature of one-dimensional voidage-wave structures has been investigated both experimentally and numerically. Responses of the bed suspension to the external harmonic forcing were also examined. Investigated features include solid vertical velocity and solid concentration. Both the experimental and numerical findings suggest that the behavior of the bed suspension is convectively sensitive to the external perturbations introduced at the bottom of the bed.


## Introduction

In practice, fluidized beds show different regimes of hydrodynamic behavior above minimum fluidization velocity. The stable, uniform and homogenous state of fluidization is seldom found in practical applications. Gas-fluidized beds are usually very unstable and the excess fluid will rise up in the form of bubbles (Clift & Grace, 1985). In liquid-fluidized beds, it is well established that it gives rise to more stable fluidization behavior and presents voidage-wave instability. Such instability was observed to be one-dimensional in narrow beds (Duru et al., 2002; Ham et al., 1990; Nicolas et al., 1996), in which case concentration plane waves propagated along the bed, with alternating dense and dilute layers; however, transverse structures (or secondary instability) were found to develop in wider beds (Duru & Guazzelli, 2002) and bubbles are conjectured to originate from such secondary instability (Anderson et al., 1995; Batchelor, 1993).

Bubbles are well known as important features in fluidized beds to induce particle motion and promote particle mixing. However, the origin of the bubble is still not well-understood. As mentioned above, bubbles are conjectured to evolve from secondary instability (or gravitational overturning instability), and this gravitational overturning instability is believed to first appear due to the first wavy disturbances (Batchelor, 1988; Batchelor, 1993; Batchelor & Nitsche, 1991). Investigations on such planar waves are essential to provide us the first step toward the fundamental understanding of bubble formation. The objective of the present study is to investigate both experimentally and numerically the nature of first type of unstable flow structure and also its responses to external harmonic forcing. Knowledge obtained from this study would provide useful insights on such multiphase systems.

## Experimental

The test system in this study has four major components: vertical cylindrical bed, rotameters, centrifugal pump and liquid tank. The experimental set-up is shown schematically in Figure 1. The bed is a glass tube of 2 cm diameter and 1 m height. The bed was fluidized by water at ambient condition. A centrifugal pump was used to circulate the water from the liquid tank through rotameters to the bed in a close loop. The bed suspension was supported by a specially-designed piston, which composed of 2 mm thick sintered stainless steel plate with orifice holes of 50 micron. Such small orifice holes are to ensure large pressure drop and uniform flow distribution. This piston could oscillate vertically at given frequency and amplitude driven by a stepper motor. Such piston-like distributor would enable us to examine the response of the bed behavior to external perturbations. The amplitude of the piston was carefully chosen as 1.5 times the particle diameter to avoid close packing in the near distributor region; in agreement with Duru et al. (2002).

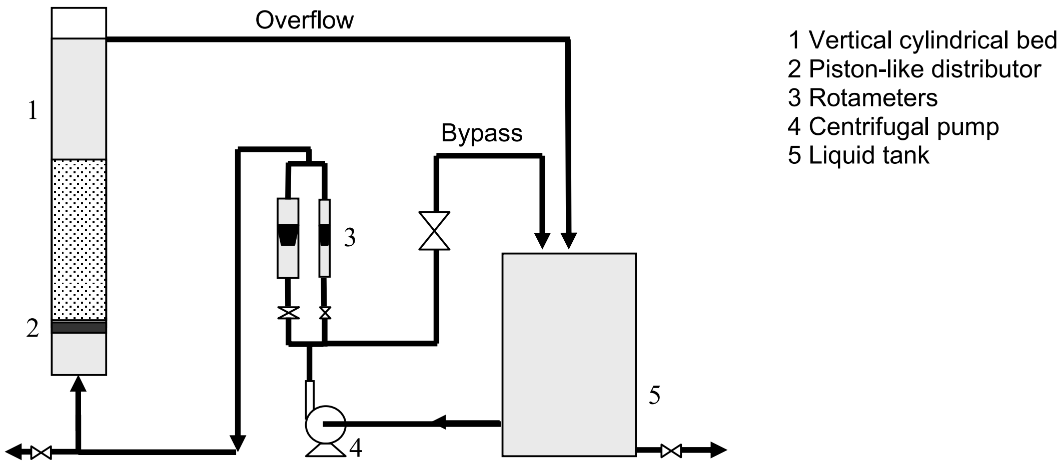



**Figure 1** Schematic diagram of the liquid-fluidized bed setup.

To ensure the smooth propagation of one-dimensional voidage-wave structures along the bed, Ham et al. (1990) and Duru et al. (2002) stated that the ratio of bed to particle diameters should be greater than 10, but should not exceed 25. Here, the granular materials used are glass beads with 2500 kg/m$^3$ density and with 1 mm diameter ($u_{mf}$ = ~0.01 m s$^{-1}$), and the corresponding bed to particle diameter ratio is 20. Typically, four regimes can be observed during experiments: packed, worming, planar wave and turbulent regimes. Our focus is on the planar wave regime. In the present study, the bed of interest was filled with glass beads up to 12 cm and fluidized by water at flow rate range 0.018-0.030 m s$^{-1}$. The bed was undergone external harmonic forcing with 1.5 mm amplitude (i.e. 1.5 times the particle diameter) and frequency range 1-2 Hz.

Solid concentrations were determined using light scattering method at various bed levels. The basic principle of this technique is that under the column backlighting condition, the light intensity transmitted through the bed suspension varies strongly as a function of solid concentration. Here, the stabilized He-Ne laser (with 25 mW energy) was used as the light source, and the low-energy type of photodiode (Newport, USA) was used to detect the transmitted intensity signals. Velocity field information of the bed was measured using a PIV (Particle Image Velocimetry) system from TSI Company. The bed was placed inside a square glass tube with area of 2.7 cm x 2.7 cm to ease the PIV measurement. New-Wave Nd:Yag lasers, operating at ~ 25 mJ/pulse, were introduced from the side wall of the square tube to illuminate particles in the bed central region. Images of the illuminated particles were acquired by a TSI camera (2K x 2K resolution) at an angle perpendicular to the laser sheet. It should be noted that the PIV sampling frequency in this study does not match the vibrating frequency of the moving piston. To solve this problem, the PIV system was operated under external trigger mode with a sampling frequency of 5 Hz. We can then obtain useful information of particle movement in one motion cycle from the images captured.

## Numerical Simulation

In the present study, the convective nature of voidage-wave instability was also investigated computationally using the Discrete Element Method (DEM) coupled with Computational Fluid Dynamics (CFD). In this method, the motion of each particle is calculated directly by taking particle-particle and fluid-particle interactions into account. Individual particle motion is traced by the direct solution of Newton's equations of motion. Whilst, the calculation of gas phase dynamics is based on local averaging of the Navier-Stokes equation. The details of the DEM model can be found in Cundall and Strack (1979) and Tsuji et al. (1993). The governing equations are given as follows:

*Particle translational motion*: $$m_i \frac{dv_i}{dt} = \sum_{j=1}^{N} \left(f_{c,ij} + f_{d,ij}\right) + m_i g + f_{f,i} \quad (1)$$

*Particle rotational motion*: $$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{N} T_{ij} \quad (2)$$

*Fluid continuity equation*: $$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon u) = 0 \quad (3)$$

*Fluid momentum equation*: $$\frac{\partial(\rho_f \varepsilon u)}{\partial t} + \nabla \cdot (\rho_f \varepsilon u u) = -\varepsilon \nabla P + \nabla \cdot (\mu_f \varepsilon \nabla u) + \rho_f \varepsilon g - F \quad (4)$$

where $m_i$ and $v_i$ are the mass and velocity of $i^{th}$ particle respectively, N is the number of particles in contact with $i^{th}$ particle, $f_{c,ij}$ and $f_{d,ij}$ are the contact and viscous contact damping forces respectively, $f_{f,i}$ is the fluid drag force due to interstitial fluid, $I_i$ is the moment of inertia of $i^{th}$ particle, $\omega_i$ is its angular velocity and $T_{ij}$ is the torque arising from contact forces which causes the particle to rotate, u is the velocity vector, $\varepsilon$ is the local average porosity, P is the fluid pressure and F is the source term due to fluid-particle interaction (Here, the fluid drag force model proposed by Di Felice (1994) was used to evaluate the drag force).

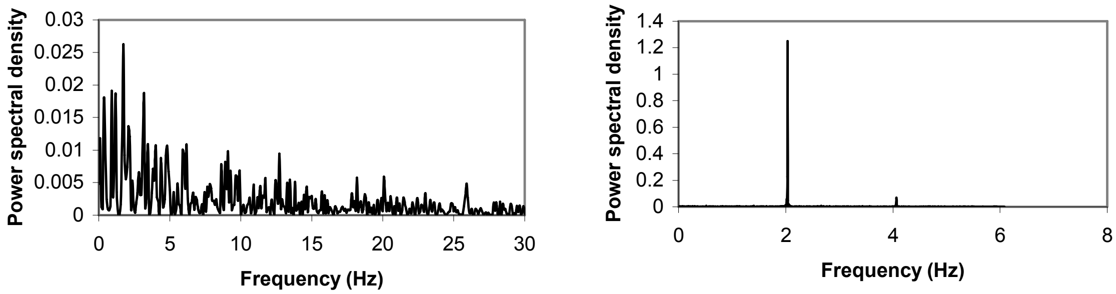
It should be noted that the normal ($f_{cn,ij}$, $f_{dn,ij}$) and tangential ($f_{ct,ij}$, $f_{dt,ij}$) components of the contact and damping forces are calculated according to a linear force-displacement model. If $\left|f_{ct,ij}\right| > \left|f_{cn,ij}\right| \tan\phi + c$, then 'slippage' between two contacting surfaces is simulated based on Coulomb-type friction law, i.e. $\left|f_{ct,ij}\right| = \left|f_{cn,ij}\right| \tan\phi + c$, where $\tan\phi$ is analogous to the coefficient of friction and c is a measure of cohesion between two contacting surfaces.

In the present study, the geometry of the simulated fluidization system consisted of a two-dimensional narrow channel of 2 cm width containing 2500 glass beads as the solid phase and water as the interstitial fluid. Each glass bead had a diameter of 1.0 mm and density of 2500 kg $m^{-3}$. The superficial velocities of the liquid used were 0.018 m $s^{-1}$ and 0.03 m $s^{-1}$. The base of the fluidization system was allowed to undergo simple harmonic motion when desired in order to facilitate the study of the effects of external perturbations on the bed stability. In case for the comparison with experimental results, the amplitude and frequency applied when a vibrating base was simulated were 1.5 times the glass bead diameter (i.e. 1.5 mm) and 2 Hz respectively.

## Results and Discussion

When the bed was operated at superficial velocity of 0.03 m $s^{-1}$ and vibrated at 2 Hz frequency and 1.5 mm amplitude, alternating dense and dilute solid concentration can be clearly seen from direct visual observations. Instead, in the absence of a vibrating base, the fluidized bed was observed to expand slightly upon introduction of liquid at the same superficial velocity and remain fluidized homogeneously with minimal tendency for the development of voidage-wave instability. This implied that the system was intrinsically less unstable in the absence of external perturbations while any internal "natural" noises (or unforced noises) were not sufficiently significant to cause harmonic instability. This can be confirmed by the power spectrum results of the solid volume fraction at 1 cm above the base in bed with and without vibration; as shown in Figure 2. Obviously, a narrow peak corresponding to the forcing frequency (2 Hz) can be found in Figure 2b. Harmonics (corresponds to the smaller peaks, particularly at 4 Hz) can also be observed in the same figure. However, the power spectrum was observed to be very broad in the absence of external perturbations (Figure 5a), confirming that the external harmonic forcing has significant direct influence on the flow behavior. This conclusion is in accordance with Nicolas et al. (1996). In the following section, quantitative analyses of this one-dimensional wave phenomenon and its comparison with the experimental results would be provided in details.

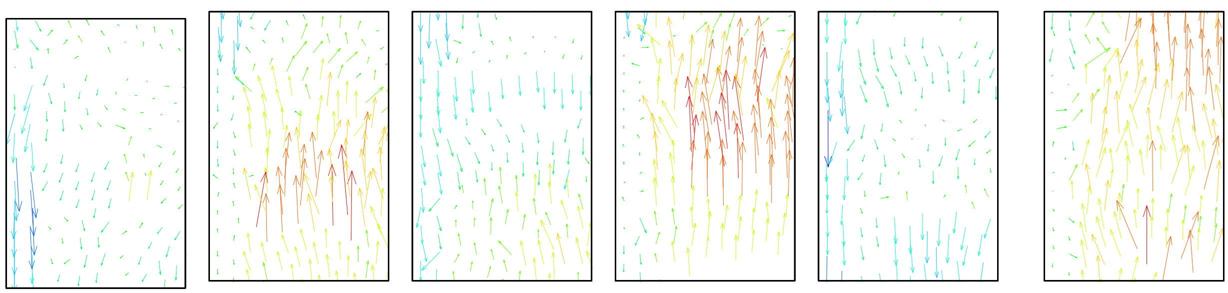
Figure 3 shows the instantaneous particle velocity vector maps in a section of the system at position 5 cm above the vibrating base using both experimental and simulation approaches, respectively. Each frame of the figure shows half a channel and has dimensions of 1.5 cm (height) by 1.0 cm (width), with one wall of the channel on the left and the centreline on the right. The frames were captured at 0.25 s intervals. These two figures illustrate the unique granular behaviour in the presence of one-dimensional voidage waves. Here, adopting an Eulerian point of view (Figure 3a), it may be seen that particles tend to switch periodically between upward and downward motions. Experiments also show more or less similar results (Figure 3b). The upward and downward motions correspond to the passage of dense and dilute phases of the voidage-wave through the particles respectively. In other words, when a dense phase of the wave propagates through a section of the bed, particles in that section were observed to be moving in the upward direction and vice versa. From the simulation approach, it seems like the characteristic length scale of the size of a dense (or dilute) region of the voidage-wave is that of the Eulerian cell used, that is, about 1.0 – 1.5 cm.



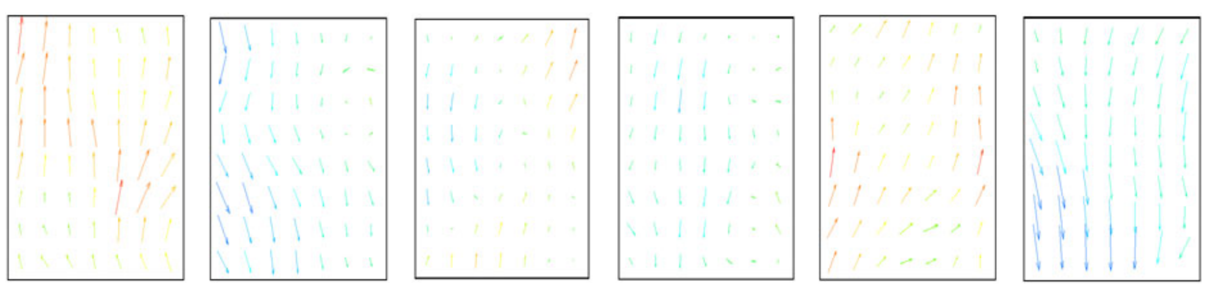

a) Without vibration

b) With vibration: f = 2 Hz, A = 1.5 mm

**Figure 2** Effect of external harmonic forcing on the power spectrum of the solid fraction profile at 1 cm above the vibrating base. Solid fraction was determined using light scattering method: glass tube with 2 cm diameter, superficial velocity of 0.03 ms$^{-1}$, base vibrating at 2 Hz frequency and 1.5 mm amplitude.



a) Simulation data



b) Experimental data

**Figure 3** Instantaneous particle velocity vector maps in a 1.5 cm (height) by 1.0 cm (width) section at 5 cm above the vibrating base. The data was shown at 0.25 s intervals. Velocity scale given by the color shading used is -0.04 m s$^{-1}$ (blue) to 0.04 m s$^{-1}$ (red).

Figure 4a shows the spatial evolution of averaged profile of the simulated vertical component of solid velocities at 5 cm above the vibrating base with respect to time. The simulation result shows quantitatively that particles oscillate periodically between upward (positive velocities) and downward (negative velocities) motions. The experimental results also show similar conclusion, as shown in Figure 5a. Though the PIV sampling frequency is different from the vibrating frequency of the base, the experimental results were found to fit the solid curve (which describes the sinusoidal motion of the particle) very well. Figure 5b shows the corresponding power spectrum of the velocity signals, obtained using the Fast

Fourier Transform (FFT) function built into the MATLAB toolbox. It may be observed that the characteristic frequency of the oscillatory solid velocity matches that of the vibrating base. This can be confirmed by the power spectrum results obtained for the experimental vertical velocity (Figure 5b).

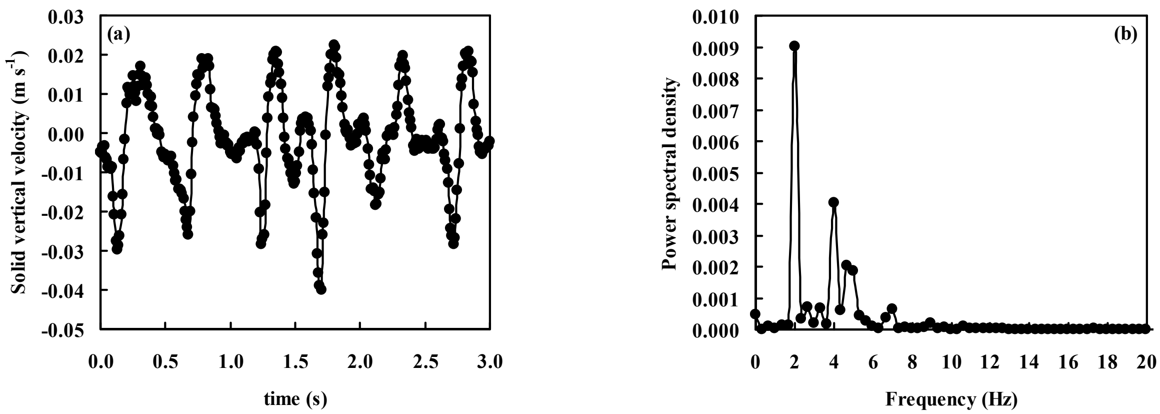



**Figure 4** Simulation data: (a) Spatial evolution of averaged vertical component of solid velocities at 5 cm above the vibrating base with respect to time; and (b) Power spectrum of the time varying solid velocities from (a).

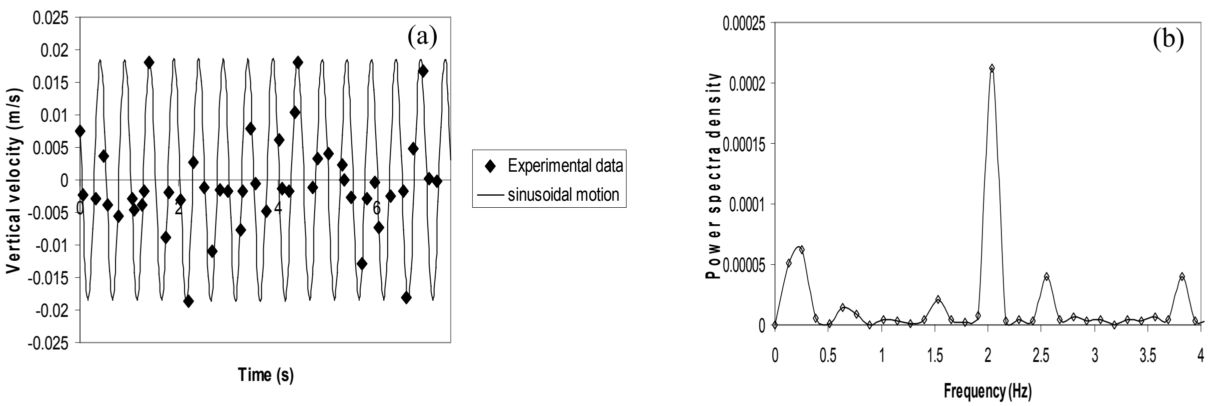



**Figure 5** Experimental data: (a) Spatial evolution of averaged vertical component of solid velocities at 5 cm above the vibrating base with respect to time; and (b) Power spectrum of the time varying solid velocities from (a).

Figures 6a and 6b show the spatial evolution of simulated average solid fraction profile at the same position (i.e. 5 cm above the vibrating base) with respect to time and its corresponding power spectrum of the solid fraction signal respectively, whereas the corresponding experimental results at the same position were presented in Figure 7. Apparently, both numerical and experimental approaches show quantitatively that the characteristic frequency of the voidage-wave is also equal to that of solid velocity, i.e. 2 Hz. In addition, there may be higher or lower harmonics in the vicinity of this characteristic frequency (in the range 1 – 5 Hz), as shown in Figures 6b and 7b.

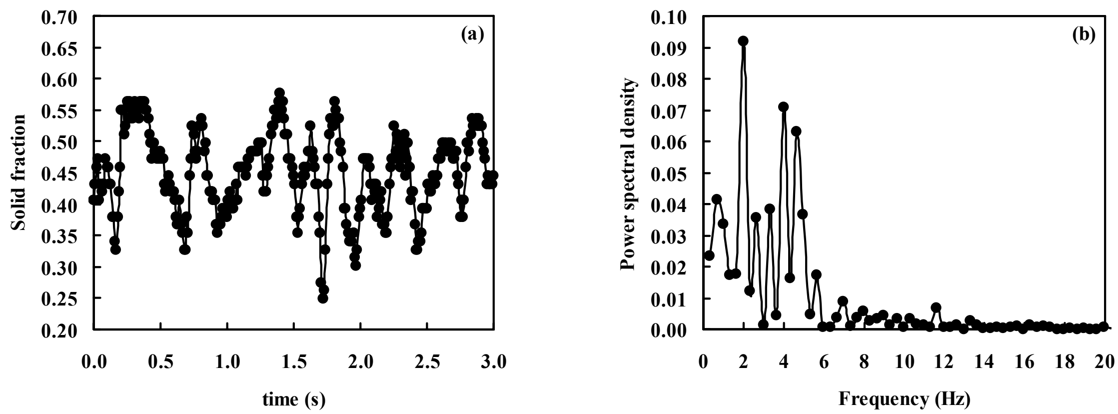



**Figure 6** Simulation data: (a) Spatial evolution of averaged solid fraction at 5 cm above the vibrating base with respect to time; and (b) Power spectrum of the solid fraction profile from (a).

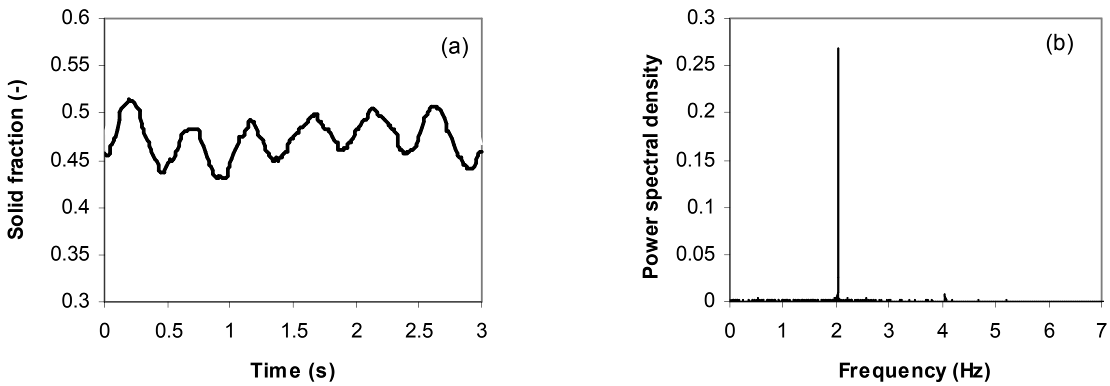



**Figure 7** Experimental data: (a) Spatial evolution of spatially averaged solid fraction at 5 cm above the vibrating base with respect to time; and (b) Power spectrum of the solid fraction profile from (a).

## Conclusions

This study investigated experimentally and numerically the characteristic of one-dimensional waves in liquid-fluidized beds. Voidage waves consisting of alternating regions of high and low solid concentrations were observed to propagate along the bed in the presence of a vibrating base. Solid particles were seen to move periodically upwards when a dense phase of the wave passed through their positions and settle periodically downwards otherwise. The characteristic frequency of such oscillatory motions of solid particles was obtained using the Fast Fourier Transform of the vertical component of solid velocities, and the motion frequency was observed to match very well the vibrating frequency of the base. Similarly, the characteristic frequency of solid volume fraction, which also exhibited periodic variations with respect to time, was found to be same as the vibrating frequency of the base. The voidage waves formed as a result of instability in such liquid-fluidized bed systems are traveling planar waves with dense and dilute phases being alternatively convected along the bed. In summary, the present work shows that the behavior of bed suspension is significantly influenced by the external harmonic forcing, and therefore should be convective in nature.

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