SCALLING OF GRANULAR TEMPERATURE IN A DENSE VIBRATED GRANULAR BED: IS PEAK VELOCITY SUFFICIENT?

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ABSTRACT

The granular temperature underpins the kinetic theory of granular flows as well as models for heat transfer, segregation, erosion, attrition and aggregation in various granular systems. We report granular temperature data of mono-disperse glass particles in a three-dimensional dense granular bed subject to vertical sinusoidal vibrations over a wide range of vibrational conditions as measured by diffusing wave spectroscopy (DWS). The granular temperature was found to scale with the square of the peak vibrational velocity in line with a number of theoretical models and experiments, but a significant correlation was observed between granular temperature and other vibrational parameters. We report here for the first time this variation of granular temperature with the various process parameters – in particular the peak vibrational velocity (from 30 to 55 mm/s), acceleration (from 1.8 to 3.4 Γ) and frequency (from 50 Hz to 170 Hz).

INTRODUCTION

Granular flow requires continuous energy supply, such as vibration, shearing or interstitial fluid flow, because of the dissipative particle collisions which are dominant in the granular flow. Such energy input results in a random motion of particles which is quantified by the so-called granular temperature, the mean-square value of velocity fluctuations around the mean flow velocity, $<\delta v^2>$ – a term first used by Ogawa (Ogawa, 1978). The granular temperature is a key property in formulating a continuum description of the flow of granular materials based on the kinetic theory of dense gases (Jenkins & Savage, 1983; Lun et al., 1984). This approach has been applied for modelling a wide range of phenomena: heat transfer (Hunt, 1997), segregation (Huilin et al., 2003), erosion (Lyczkowski & Bouillard, 2002), attrition (Campbell, 1994) and aggregation (Tan et al., 2006) in various particle processing technologies.

Vibration of granular media occurs widely in technology (e.g. sorting of minerals) and nature (e.g. earthquakes). Many studies of such systems have focussed on the scaling of the granular temperature with particular emphasis on vibrational peak velocity. Kinetic theory considerations of a vibrated bed suggest a granular temperature scaling with the square of the peak velocity (Warr et al., 1995; Kumaran, 1998). The majority of experimental studies in highly fluidized two-dimensional (2D) (Feitosa & Menon, 2002; Tai & Hsiau, 2004) and dilute three-dimensional (3D) vibrated granular system (Losert et al., 1999; Falcon et al., 2006; Wang et al., 2009) confirmed the theoretical prediction. On the other hand, some

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experimental studies suggest a power law relation with an exponent around 1.5 (Warr et al., 1995; Wildman et al., 2001; Wildman & Huntley, 2003) similar to numerical simulation results (Luding et al., 1994). Two more recent experimental studies of the granular temperature scaling in highly dense 3D vibrated granular bed were also, however, in line with theoretical prediction (You & Pak, 2001; Zivkovic et al., 2008).

Despite the many earlier findings suggesting the granular temperature in vibrated granular media scales with the square of the peak velocity only, recent very careful experiments by us using the highly sensitive and flexible method of Diffusing Wave Spectroscopy (DWS) method have lead us to discover that granular temperature is not completely independent of acceleration. This finding is reported here. We first outline the experimental details, including an overview of DWS and details pertaining to the apparatus and the particulate materials, and the experimental procedures used. This is followed by presentation of the results obtained, which includes scaling of the granular temperature with acceleration at a fixed peak velocity and mapping of granular temperature with the peak velocity and acceleration.

EXPERIMENTAL DETAILS

Experimental apparatus

The experimental apparatus is illustrated in Fig. 1. The granular material was held in a thin rectangular column with smooth plexiglass walls, fixed so that only vertical motion was possible. The column inner cross-section was 15 x 200 mm, and its height was 500 mm. The column was filled with semi-transparent spherical glass particles of diameter d = 0.95 ± 0.05 mm to a mean granular bed height, h = 75 mm. The degree of expansion of the granular bed was minute (less than 1 mm in all experiments performed) and practically impossible to measure. However, even this invisible dilation provided enough free volume for the particles to flow. For example, if we assume the expansion of the system to be 1 mm, we can estimate that the free volume for particles movement is only around 2 % of the particles' actual volume but is still enough to allow flow, in line with previous practical experience (Petekidis et al., 2002). Thus, the solid volume fraction of the granular system is slightly less than the random close packing limit of 0.64.

The bed, including the container, was subject to vertical vibrational forcing provided by an air-cooled electromagnetically driven shaker (V721, LDS Ltd., Hertfordshire, UK). The vibrational forcing was controlled by a Dactron COMET USB controller (LDS Ltd.) with feedback from two integrated-circuit piezoelectric accelerometers (model 353B03, PCB Piezotronics Inc., NY, US) attached to the base of the column. The acceleration and frequency were controlled to a resolution of 0.005 g and 0.01 Hz respectively.

The dynamics of the particles in the vibrated bed were studied using DWS in transmission mode (Weitz & Pine, 1993). This method involves illuminating one side of the bed at the point of interest with an ~2 mm diameter laser beam and collecting the scattered light from the opposite side of the bed over a time, t, with a single mode optical fibre (OZ Optics Ltd., Ottawa, Canada). A 400 mW diode pumped solid state linearly polarized laser (Torus 532, Laser Quantum Ltd., Cheshire, UK), operating at a wavelength of 532 nm in single longitudinal mode, was used. The collected light signal was bifurcated and fed into two matched photomultiplier tubes (PMTs) to reduce spurious correlations due to possible after-pulsing effects of the detector. The outputs from the PMTs were amplified and fed to a multi-tau digital correlator (Flex 05, Correlator.com, US), which performed a pseudo cross-correlation analysis in real time to give the intensity autocorrelation function (IACF), $g_2(t)$, that was stored on a PC for further offline analysis as detailed below.

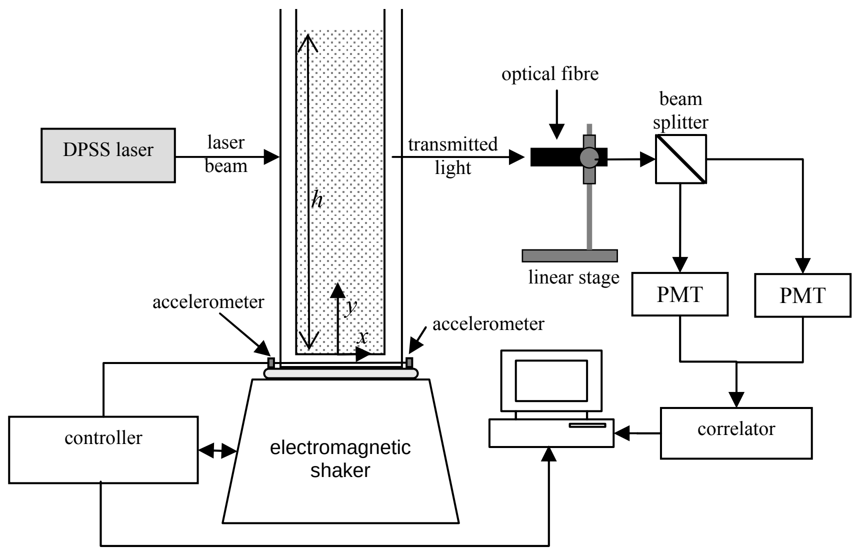

Fig. 1. Schematic of the experimental setup.

Experimental procedure

The vibrated bed was subject to sinusoidal vibrations in all cases reported here. The vertical position of the bed, at time t, for such vibrational motion is expressed by

$$y_p = A\sin(\omega t) \tag{1}$$

where A and $f = \omega/2\pi$ are the amplitude and frequency respectively. The associated peak vibrational velocity and acceleration of the bed are $v_p = \omega A$ and $a_p = \omega^2 A$ respectively; the latter is presented here in the non-dimensional form, $\Gamma = a_p/g$, where g is the acceleration due to gravity. Note that frequency, amplitude, velocity and acceleration are related. Knowing any two quantities, other variables can be easily calculated.

The IACF was determined at the centerline of the bed, $x = 0$ mm, and at vertical position, $y = 40$ mm above the base of the bed which is approximately center of the bed. The measurements were done at only one position as our previous experiments found that the granular temperature varied very little with spatial position in the bed (Zivkovic et al., 2008). Measurements near the wall, the top and bottom of the bed where variations may be expected were impossible due to experimental constraints (Zivkovic et al., 2008; Zivkovic et al., 2009a). Before each measurement the system was vibrated for at least 10 minutes, allowing the bed to reach a stationary state. The IACFs were obtained by collecting and correlating ten blocks of data of 30 s long each.

The normalized electric-field autocorrelation function (FACF), $g_1(t)$, was obtained from the IACF, $g_2(t)$, using the Siegert relationship (Berne & Pecora, 1976; Weitz & Pine, 1993)

$$g_2(t) \equiv \frac{\langle I(0)\rangle\langle I(t)\rangle}{\langle I\rangle^2} = 1 + \beta|g_1(t)|^2 \tag{2}$$

where β is a phenomenological parameter determined from the intercept of the IACF; this phenomenological parameter was always found to be $\beta \approx 0.5$, as expected for depolarized light (Weitz & Pine, 1993).

The mean square displacement (MSD) of the particles, $<\Delta r^2(t)>$, was determined by inverting the FACF using the formula (Weitz and Pine 1993)

$$g_1(t) = \frac{\frac{L/l^* + 4/3}{z_0/l^* + 2/3}\left[\sinh\left(\frac{z_0}{l^*}\sqrt{X}\right) + \frac{2}{3}\sqrt{X}\cosh\left(\frac{z_0}{l^*}\sqrt{X}\right)\right]}{(1+\frac{4}{9}X)\sinh\left(\frac{L}{l^*}\sqrt{X}\right) + \frac{4}{3}\sqrt{X}\cosh\left(\frac{L}{l^*}\sqrt{X}\right)} \tag{3}$$

where $X = <\Delta r^2>k^2 + 3l^*/l_a$, L is the sample thickness (15 mm here), l^* the transport mean free path, l_a the absorption path length, $z_o = \gamma l^*$, the distance over which the incident light is randomized, and $k = 2\pi/\lambda$, the light wave vector. The scaling factor, γ, was set to unity in line with common practice (Weitz & Pine, 1993; Xie et al., 2006).

The particle velocity fluctuations about the mean flow velocity (*i.e.* the granular temperature to within a constant) can be derived straightforwardly from the ballistic region of the MSD (Menon & Durian, 1997), provided it is resolved, using the expression

$$\langle \Delta r^2 \rangle = \langle \delta v^2 \rangle t^2 \tag{4}$$

Equation 3 requires knowledge of the transport mean free path, l^*, or step size in the random walk of photons, and the diffusive absorption path length, l_a, which accounts for light absorption, at the positions and conditions considered. In our previous study (Zivkovic et al., 2008), we determined that l_a = 4 mm and l^* is a function of the amplitude (around 2 mm) using the method of static transmission (Weitz & Pine, 1993; Leutz & Rička, 1996).

RESULTS AND DISCUSSION

Fig. 2 shows a typical intensity autocorrelation function (IACF), $g_2(t)$, along with the electric-field autocorrelation function (FACF), $g_1(t)$, and mean square displacement (MSD), $<\Delta r^2(t)>$, obtained from the analysis outlined in previous section. The example IACF, shown in Fig. 2 (a), first decays from $g_2 \approx 1.5$ over the timescale of $10^{-6} \sim 10^{-5}$ s to an intermediate plateau where it remains before once again decaying over the timescale of $10^{-1} \sim 10^{0}$ s, this time towards unity. The intercepts of g_2 for all considered vibrational conditions were close to 1.5, the expected value for depolarized light (Weitz & Pine, 1993). This value indicates that we are imaging one coherence area and that enough decorrelation cycles have been taken to ensure good statistics.

Fig. 2(b) shows that the double decay and timescales seen in the IACF are reflected and enhanced in the FACF, as one would expect given the Siegert relationship, equation 2. Rigorous interpretation of the long time behaviour is difficult due to limitations of the technique (Zivkovic et al., 2009b). However, previous work by us (Zivkovic *et al* 2008) suggests that it is reasonable to attribute the intermediate plateau and second decay in the ACFs of Fig. 2 to caged motion of particles at intermediate times and, at longer times, particles breaking free of their cages only to become trapped once again in new cages nearby. The mean square displacement obtained from inversion of equation 3 using the FACF is shown in Fig. 2 (c). Quantitative analysis of the ballistic region of this MSD using equation 4 gives a particle velocity fluctuation $\langle \delta v^2 \rangle^{1/2}$ = 2.86 mm/s. The intermediate plateau in MSD can not be used for quantitative analysis due to the limitations of the technique which is the reason we did not show MSD for times longer than 0.1 millisecond (Zivkovic et al., 2009b).

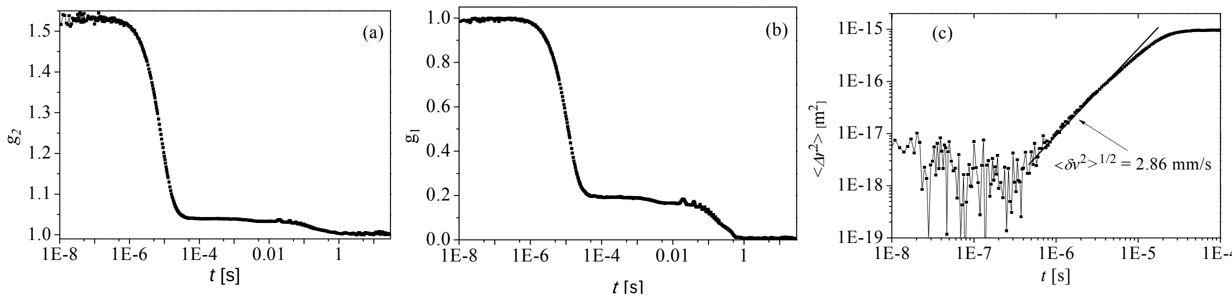

Fig. 2. (a) The intensity autocorrelation function, $g_2(t)$, at Γ = 2.6 and v_p = 40 mm/s. (b) The normalized electric-field autocorrelation function, $g_1(t)$, obtained from $g_2(t)$ using the Siegert relationship. (c) The mean square displacement obtained from $g_1(t)$ by inverting eq. 3; the mean fluctuating velocity, $\langle \delta v^2 \rangle^{1/2}$ is indicated. The solid line is fit to eq. 4.

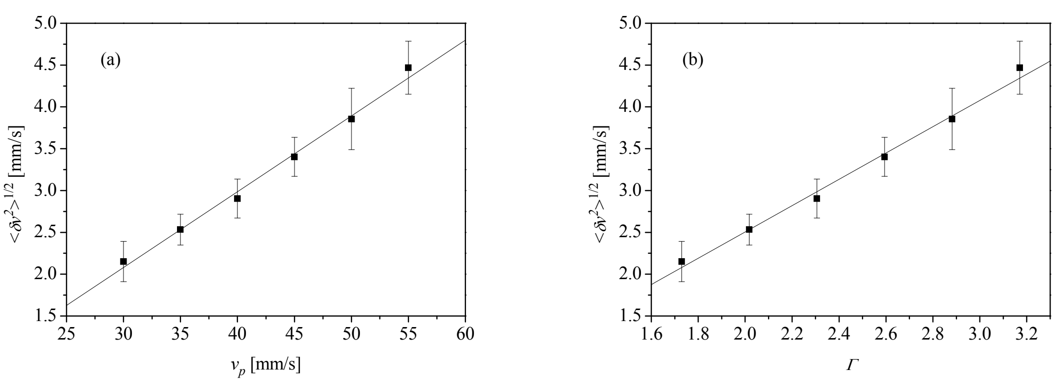

Fig. 3. Variation of the mean velocity fluctuations about the mean, $\langle \delta v^2 \rangle^{1/2}$, with peak forcing velocity, v_p, and accelerations, Γ, at fixed frequency f = 90 Hz. Error bars are standard deviations of the ten correlation measurements and lines are a linear fit to the data.

Most experimental studies of the granular temperature scaling in a vibrated granular bed are carried out at a fixed frequency (Warr et al., 1995; Wildman et al., 2001; You & Pak, 2001; Feitosa & Menon, 2002; Wildman & Huntley, 2003). Fig. 3(a) shows that the velocity fluctuation is linear function of the peak vibrational velocity at a fixed frequency, which is inline with the theoretical prediction that the granular temperature scales with the square of the peak velocity (Warr et al., 1995; Kumaran, 1998). Yet, a linear trend is also obvious when the granular temperature data is re-plotted against acceleration (Fig. 3(b)), which is expected as acceleration is linear function of peak velocity at a fixed frequency (*viz.* $\Gamma = 2\pi f v_p$). Thus, the commonly used experimental protocol is flawed as it cannot elucidate influence of acceleration on the granular temperature. Linear fitting gives slopes of 0.091 and 1.57 for scaling of the fluctuation velocity with peak velocity and acceleration respectively (adjusted coefficient of determination for both linear fitting $R^2 = 0.9891$) – we shall return to this later.

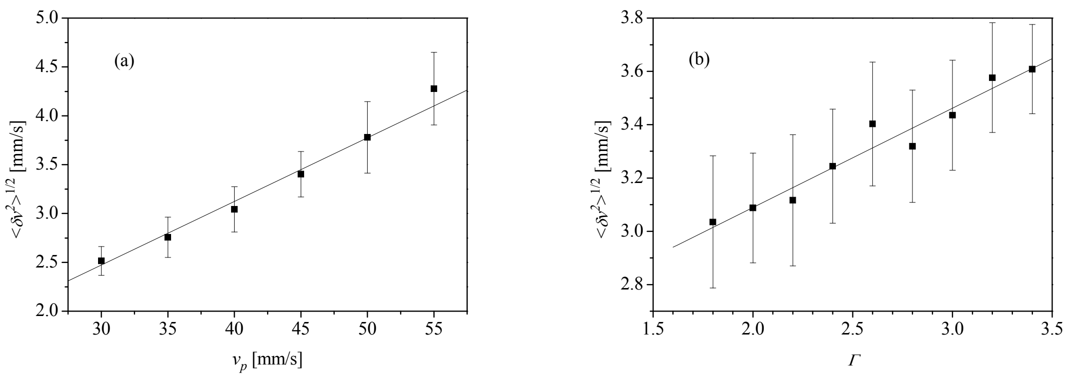

Fig. 4. The mean velocity fluctuations about the mean, $\langle \delta v^2 \rangle^{1/2}$, dependence with the peak vibrational velocity at fixed dimensionless acceleration Γ=2.6 (a) and with acceleration at fixed peak vibrational velocity v_p = 45 mm/s. Error bars are standard deviations of the ten correlation measurements and lines are a linear fit to the data.

Therefore, we explored vibrational parameter set systematically and performed experiments at fixed peak velocity (varied acceleration) and at fixed acceleration (varied peak velocity) to decompose influence of these two parameters on the granular temperature scaling. Fig. 4 shows that the granular temperature data obtained by DWS here shows a linear dependence with both peak velocity and acceleration when other parameter is kept constant. Although a linear relationship between $\langle \delta v^2 \rangle^{1/2}$ and peak velocity is expected, Fig. 4(b) shows that the fluctuation velocity for a given peak vibrational velocity, v_p, is not constant at all but, rather, there is a correlation with the vibrational acceleration, Γ. Although not previously commented on, careful consideration of the data from previous studies where the granular temperature tends to be higher for elevated accelerations (Losert et al., 1999) and frequencies (Tai & Hsiau, 2004) in fact supports this dependence on acceleration. This lack of comment on the dependence we observe here despite it being evident at least in part is not perhaps unsurprising because of the relatively high experimental uncertainties in measurement of the granular temperature and the tedious nature of the experiments, which limited determination to one point per set of vibrational parameters. On the other hand, the opposite tendency is prevailing of lower granular temperature at elevated acceleration in our previous experiments for similar granular systems (Zivkovic et al., 2008). The reason for this contradiction is probably the difference in the excitation mechanism - while in the study reported here we vibrated the whole box as in the experiments of Loser et al (1999) and Tai & Hsiau (2004), in our previous study (Zivkovic et al., 2008) we vibrated the base of the bed only (i.e. the side walls were stationary). Further experimental investigation is necessary to further elucidate this origin for the difference and the role played by boundary conditions on the granular temperature scaling.

The experimental data shows linear dependence and is described very well by straight lines of slope 0.067 (R^2 = 0.9798) and 0.37 (R^2 = 0.9510) for velocity and acceleration respectively. The velocity scaling factor changed moderately (decreased from 0.091 to 0.067), but acceleration scaling factor changed considerably (from 1.57 to 0.37) in comparison with experiments where frequency was fixed. This shows that peak velocity is the leading parameter in scaling of granular temperature in vibrated granular media, but influence of acceleration is still significant and can not be neglected. Therefore, we plotted granular temperature as a function of both peak velocity and acceleration.

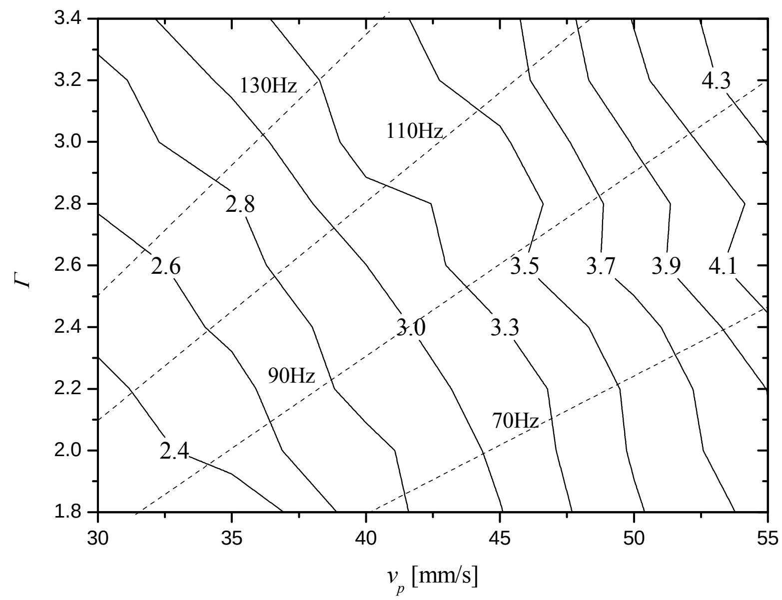

Fig. 5. Contour plot of the particle fluctuation velocity, $\langle \delta v^2 \rangle^{1/2}$ in mm/s, in the vibrated bed as a function of the peak vibrational velocity, v_p, and the dimensionless acceleration, Γ. Solid lines are granular isotherms; iso-frequency lines are dashed.

Fig. 5 shows the first-ever to our knowledge of a map of the granular temperature as a function of the peak vibrational velocity and the acceleration. The curvature of granular isotherms indicates the minor non-linearity. Indeed, a quadratic model fitting (R^2 = 0.9880) is reasonably better than the linear models with (R^2 = 0.9676) or without (R^2 = 0.9674) cross-term (i.e. the bilinear term v_pf). On the other hand, iso-frequency lines intersect with granular isotherms at more or less constant angle, almost perpendicular. This implies that iso-frequency lines are close to a path of steepest ascent which explains higher slope of granular temperature scaling with velocity for fixed frequency compared to fixed acceleration experiments. It also suggests that frequency may be a better parameter than acceleration for scaling granular temperature.

Fig. 6 show map of the granular temperature as a function of the peak velocity and the frequency. The data is fitted with linear model to give following scaling relation

$$\langle \delta v^2 \rangle^{1/2} = 0.0921 v_p + 0.0124 f - 1.867 \quad (5)$$

where R^2 = 0.9814. The adjusted coefficient of determination, R^2, is the same when the cross-term is included, indicating it is unnecessary. Addition of quadratic terms increases R^2 to 0.9881, but this is probably a result of considerable experimental noise. Comparison with linear model using the acceleration as the second parameter shows considerable improvement (R^2 increased from 0.9676 to 0.9184), showing this is the most suitable model for granular temperature in a dense vibrated bed.

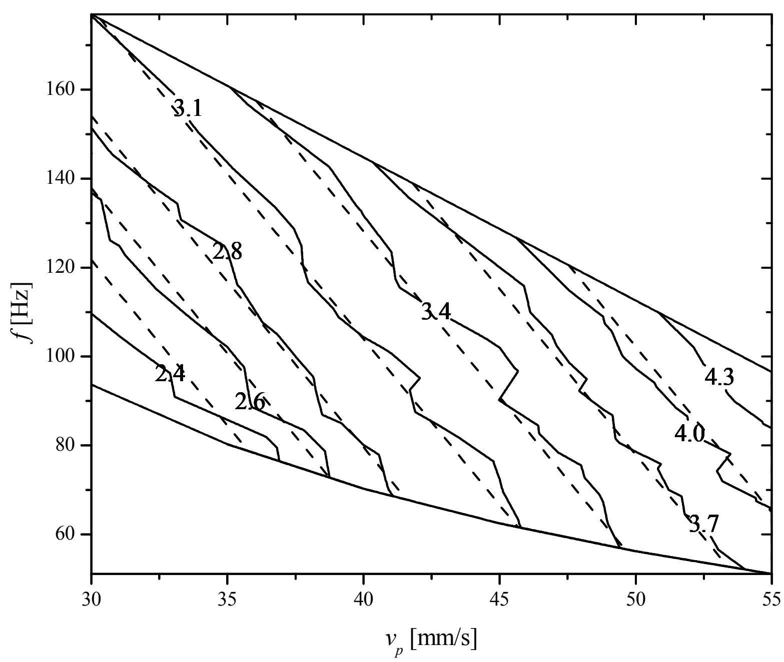

Fig. 6. Contour plot of the particle fluctuation velocity, $\langle \delta v^2 \rangle^{1/2}$ in mm/s, in the vibrated bed as a function of the peak vibrational velocity, v_p, and the frequency, f. Solid lines are experimental granular isotherms; linear model fitting lines are dashed, equation 5.

CONCLUSION

Diffusing wave spectroscopy, which is a highly sensitive yet versatile method relative to methods used previously to measure granular temperature, has been used to measure particle velocity fluctuations, $\langle \delta v^2 \rangle^{1/2}$, of 0.95 mm glass particles in a dense three-dimensional vibrated granular bed. We have determined the variation of the granular temperature of particles with sinusoidal vibrational conditions. Although it was found the square of the peak vibrational velocity is the leading parameter in scaling of granular temperature in line with theory and previous experiments, a significant correlation was observed with other vibrational parameters. Statistical analysis showed that the frequency is a slightly better second parameter, the first one obviously being peak velocity, for mapping the granular temperature. Future experiments should be undertaken to see if the results obtained here are retained when various other system parameters (e.g. granular bed height and restitution coefficient) are varied.

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BRIEF BIOGRAPHY OF PRESENTER

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