Ultrasonic Correlation Spectroscopy: new techniques for the Nondestructive Evaluation of strongly scattering media

J. H. Page[a], M. L. Cowan[a] and D. A. Weitz[b]

[a]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2, Canada*
[b]*Department of Physics and DEAS, Harvard University, Cambridge, MA 02138*

Two new techniques in ultrasonic correlation spectroscopy, Dynamic Sound Scattering and Diffusing Acoustic Wave Spectroscopy, are described. Their potential for characterizing the dynamics of strongly scattering materials is illustrated with experimental data on the motion of particles in fluidized beds.

Recent progress in understanding the propagation of acoustic waves in strongly scattering materials [1,2] has facilitated the development of two new techniques in ultrasonic correlation spectroscopy [3]: Dynamic Sound Scattering (DSS) and Diffusing Acoustic Wave Spectroscopy (DAWS). These techniques provide sensitive and complementary probes of the dynamics of such systems, where direct imaging of the individual scatterers (e.g. particles or inclusions) may become impossible due to the dominance of acoustic speckle. Rather than regarding speckle as a deleterious effect, these techniques exploit the existence of speckle to obtain information on the scatterer dynamics, by measuring and analysing the temporal fluctuations that occur in a speckle pattern whenever the scatterers are moving. Using correlation spectroscopy, the motion of the scatterers can be measured even when the variance exceeds the mean velocity of the scatterers, yielding a wide range of dynamic information that has not previously been obtained in ultrasonic scattering experiments. In this paper, we outline the basic principles behind DSS and DAWS, illustrating their potential as nondestructive evaluation techniques with experimental results on the dynamics of fluidized beds.

In our experiments, we study a simple realization of fluidized beds in which 1-mm-diameter glass beads are suspended in water-glycerol mixtures by flowing the liquid upward to counteract gravity-induced sedimentation. Even though the average velocity of the particles is zero, they are far from stationary, one of the most important dynamic quantities being their root mean square (rms) velocity V_{rms}. To characterize its behaviour, we use Dynamic Sound Scattering, which determines V_{rms} from the fluctuations of ultrasonic waves that are scattered once off the particles (single scattering limit). Fig. 1(a) shows an example of a short segment of these temporal field fluctuations, $y(t)$, measured in a single speckle spot. The motion of the scattering particles that causes these field fluctuations is determined in DSS by calculating the temporal field autocorrelation function, $g_1(t) = \int y^*(t)y(t+t)dt \,/\, \int |y(t)|^2 dt$, which is shown in Fig. 1(b) for the data illustrated in Fig. 1(a). To ensure that a good measurement of $g_1(t)$ is obtained, it is calculated here using a Fast Fourier Transform method from fifty 131,000-point digitized records of $y(t)$. The decay of the autocorrelation function is caused by the increase with time in the phase of the scattered field, which can be directly related to the mean square displacement of the particles $\langle \Delta r^2(t) \rangle$. In DSS this

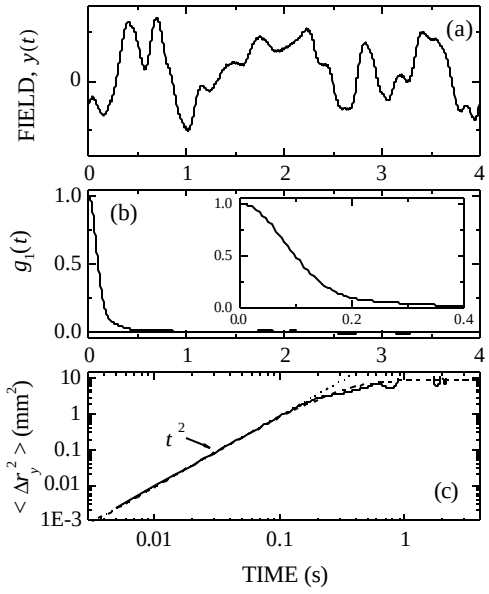

FIGURE 1. (a) Ultrasonic field fluctuations, (b) field auto-correlation function (inset shows the early time behaviour) and (c) single-particle mean square displacements in a fluidized bed, measured using Dynamic Sound Scattering.

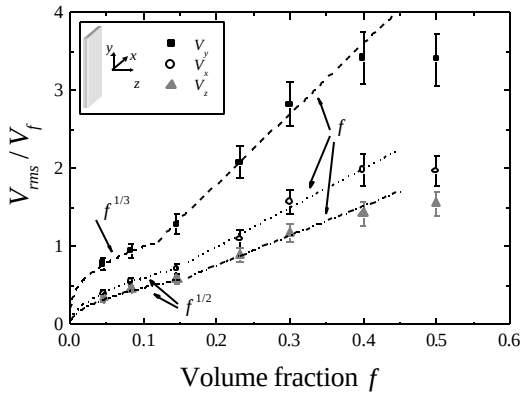

FIGURE 2. Volume fraction dependence of all 3 components of the rms particle velocity, normalized by the fluidization velocity V_f, in a fluidized suspension of glass beads. The particle Reynolds number is 0.9.

relationship gives $g_1(t) = \exp[-q^2\langle\Delta r_i^2(t)\rangle/6]$, where $q \equiv |\boldsymbol{k} - \boldsymbol{k}'| = 2k\sin(q/2)$ is the scattering wave vector, $\boldsymbol{k}$ and $\boldsymbol{k}'$ are the incident and scattered wave vectors in the medium, q is the scattering angle, and the subscript i in $\langle\Delta r_i^2(t)\rangle$ denotes the component parallel to $\boldsymbol{q}$. By measuring the field fluctuations at a particular scattering angle and direction of $\boldsymbol{q}$, any of the three orthogonal components of $\langle\Delta r^2(t)\rangle$ can be determined, as shown in Fig. 1(c) for the vertical (y) component (parallel to the fluid flow direction). At early times, $\langle\Delta r_y^2(t)\rangle$ increases quadratically with time, indicating ballistic particle motion with $\langle\Delta r_y^2(t)\rangle = \langle\Delta V_y^2\rangle t^2$; thus the y component of V_{rms} can be directly determined from Fig. 1(c). Figure 2 compares the volume fraction dependence of V_{rms} along all three directions perpendicular to the faces of the bed, giving important new information on the anisotropy in the velocity of fluidized particles. At later times, $\langle\Delta r_i^2(t)\rangle$ increases more slowly as the collective flow patterns (swirls) modify the single particle trajectories. This behaviour is well described by the relation $\langle\Delta r_i^2(t)\rangle = \langle\Delta V_i^2\rangle t^2/[1+(t/t_c)^{2-m}]$ (dashed curve in Fig. 1(c)), allowing the correlation time t_c and the dynamic correlation length $d_c = V_{rms}\, t_c$ to also be measured. This example shows how DSS can give important information on both the single-particle and collective dynamics of fluidized suspensions.

To learn more about the particle dynamics, we have developed another technique called Diffusing Acoustic Wave Spectroscopy [3]. This technique uses multiply scattered ultrasound [1, 2] to determine the *relative* motion of particles that are separated, on average, by a distance equal to the ultrasonic mean free path l^*. Since the mean free path can be varied by varying the ultrasonic frequency, DAWS can be used to probe the local relative motion of the particles over a range of length scales, down to the nearest-neighbour

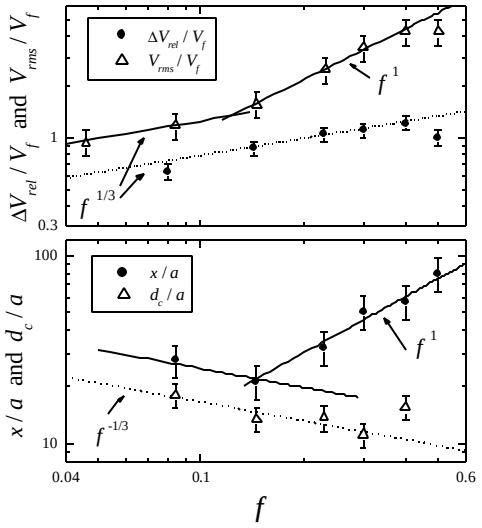

FIGURE 3. Comparison of (a) ΔV_{rel} (solid symbols) with V_{rms} (open symbols), and (b) x (solid symbols) with d_c. (open symbols).

separation of the particles. In Fig. 3(a), DAWS measurements of the local relative velocity ΔV_{rel} at the interparticle separation are compared with DSS measurements of the total rms velocity V_{rms}. As the length scale l^* is increased, ΔV_{rel} also increases, reaching a maximum value of $\sqrt{2}V_{rms}$ at the instantaneous velocity correlation length x. Thus the correlation length x, which determines the size of the complex correlated flow patterns that are characteristic of fluidized suspensions, can also be measured by combining DSS and DAWS. Fig 3(b) compares the instantaneous and dynamic correlation lengths, x and d_c; since $d_c < x$ these data show that the lifetime of the swirls is quite short, as the particles can only travel a fraction of x before their velocities become decorrelated. These experiments illustrate the wealth of information that can be obtained nondestructively using these spectroscopic techniques, suggesting that DSS and DAWS may have important future uses for both fundamental studies and practical applications.

Acknowledgement is made to NSERC for support of this research.

REFERENCES

1. J. H. Page, H. P. Schriemer, A. E. Bailey, and D. A. Weitz, *Phys. Rev. E* **52**, 3106-3114 (1995).

2. H. P. Schriemer, M. L. Cowan, J. H. Page, P. Sheng, Z. Liu, and D. A. Weitz, *Phys. Rev. Lett.* **79**, 3166-9 (1997).

3. M. L. Cowan, J. H. Page, and D. A. Weitz, *Phys. Rev. Lett.* **85**, 453-456 (2000).