SONIC CLEANING USING LASER-GENERATED SHOCKS

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1 INTRODUCTION

There has been considerable work on the use of sound for de-bonding and dispersal of particulates. Where the fluid medium involved is air, previous work has emphasized the use of high-intensity low-frequency sound[1]. This has the advantage that in many industrial applications the source may be positioned at significant distances from the surfaces to be cleaned. The mechanisms of sonic cleaning in air are not fully understood[1]. The primary force exerted by a sound wave on a fixed spherical particle of diameter d_p is given by[2]

$$F_s(\omega) = 3\pi\eta d_p \left| 1 + \frac{d_p}{2\delta(\omega)} - i\frac{d_p}{2\delta(\omega)}\left(1 + \frac{2}{9}\frac{d_p}{2\delta(\omega)}\right)\right| u, \qquad (1)$$

where η is air viscosity, u is relative air-particle velocity, $\delta(\omega) = \sqrt{\frac{2\eta}{\omega\rho_0}}$ is the viscous boundary layer thickness, ρ_p is particle density and ρ_0 is air density.

The normal component of the (maximum) adhesive force between a 'large and soft' spherical particle of diameter d_p and the surface, i.e. the negative load necessary to break the contact is[3]

$$F_a^{ls} = \frac{3}{4}\pi\gamma d_p, \qquad (2a)$$

where γ is the surface adhesion energy.

For 'small and hard' particles[3],

$$F_a^{sh} = \frac{2}{3}F_a^{ls}. \qquad (2b)$$

The surface energy is determined from experiments on the particle-surface system in question. In general it is between 0.001 and 0.1 J m^{-2}. The condition for particle separation from the surface is

$$F_s(\omega) > F_a. \qquad (3a)$$

which can be rewritten as:

$$u > \frac{\gamma}{n\eta\left|1+\frac{d_p}{2\delta(\omega)} - i\frac{d_p}{2\delta(\omega)}\left(1+\frac{2}{9}\frac{d_p}{2\delta(\omega)}\right)\right|} . \qquad (3b)$$

where n is 4 for 'large, soft' particles and 6 for 'small hard' ones.

While the particle is not detached from the surface it is not moving, so the relative velocity *u* is equal to the particle velocity in the sound wave. If it is assumed that the relationship between pressure and velocity in the sound wave is close to that in air ($p = u\rho_0 c$), then (3b) allows prediction of the sound pressure required to separate an isolated particle of a given size from a surface. Figure 1 shows predictions as a function of frequency of the 'minimum' sound pressure *p* to remove 'small hard' particles with surface energy $\gamma = 0.001 Jm^{-2}$ and for three different particle sizes (1- $d_p = 100\mu$m, 2- $d_p = 10\mu$m, 3- $d_p = 1\mu$m).

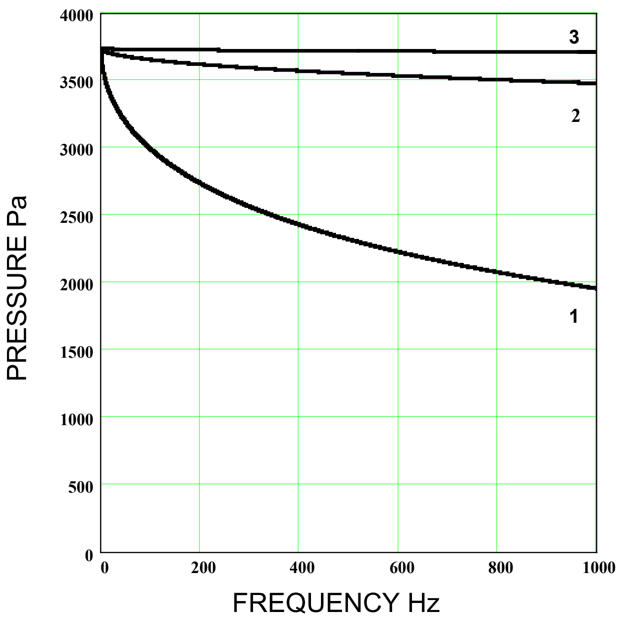


Figure 1 Predictions of the acoustic pressure required to remove isolated 'small hard' particles with different diameters (1 – 100μm, 2 – 10μm and 3 – 1µm) from a surface.

For $\gamma = 0.001 Jm^{-2}$, the minimum sound pressure necessary to separate a small hard $1\mu m$ diameter particle from a surface is predicted to be close to 3.75 kPa (SPL = 165 dB re 20μPa) and is almost frequency independent. For the largest particle size considered (100 μm), the predicted minimum sound pressure is significantly lower at 1kHz, i.e. 2 kPa (SPL = 160 dB re 20μPa) than at 100 Hz and decreases with increasing frequency. The predicted minimum sound levels for overcoming surface adhesion are comparable with those used in experiments in which 20/30 glass beads were removed from glass slide surfaces using 1 kHz tone bursts[4]. This suggests that sonic cleaning of particle-encrusted surfaces in air should be effective when using relatively high audio-frequencies even though this would reduce the distance required between source and surface to be cleaned compared with use of high-power low-frequency sound.

When a high-power laser beam is focused at a point, the air at the focal point is heated to temperatures of thousands of degrees within several nanoseconds and breaks down. This generates a spark that, in turn, is accompanied by an acoustic shock wave. Comparisons and analysis of many waveforms has shown that the acoustic pulses associated with the laser-induced sparks are more repeatable and have higher intensity than those from an electrical spark source. At 3 cm from the laser-generated spark, the acoustic spectrum peaks at 20 kHz and has a peak level of the order of 180 dB[5]. The peak frequency decreases rapidly with distance over the first few centimetres. It is approximately 10.5 kHz at 20 cm from the laser-generated spark. Experiments have been conducted using laser-generated acoustic shocks to remove fly ash particles, compacted to various degrees, from a dish that was vertically mounted at a distance of between 10 and 20 cm from the sparks. The dependence of the removal rate on degree of compaction and intensity has been explored. Accelerometer measurements have confirmed that the main mechanism involves the direct action of the acoustic shockwaves on the particle bonding rather than vibration induced in the sample holder.

2 EXPERIMENTS

The laser used to generate the sparks was a Q-switch Surelite III-10 Nd: YAG laser with a 1064 nm wavelength and a power of 800 MJ per pulse. Without focussing, the diameter of the laser beam is 9mm and the intensity of the laser pulse is $2.07 \sim 3.14\times10^{8}$ W/cm^2. This intensity is much lower than the threshold of 10^{11} W/cm^2 required to break down the air. A convex lens can be used to focus the beam to a spot of diameter of about 0.3mm so that the light intensity in the focused spot is between 1.88×10^{11} and 2.83×10^{11} W/cm^2. In the experiments reported here, the laser beam was focused using a lens with a focal length of 10cm. The gas breakdown induced by the focussed laser beam has duration of between 4 and 6 nanoseconds. Figure 1 shows an example of the resulting shock waveform and corresponding spectrum measured using an 1/8″ microphone at a distance of 3 cm from the spark.

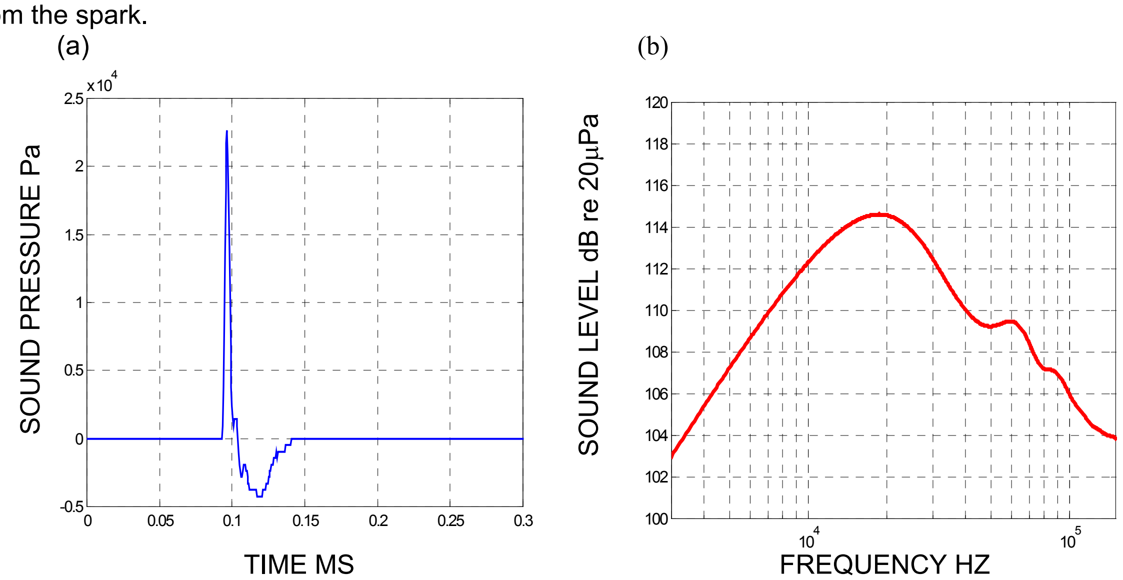


Figure 2 Characteristics of laser-generated acoustic shocks at 3 cm from the optical spark

Experiments have been conducted using the laser-generated shocks to remove particles from a vertically mounted dish covered with compacted fly ash. The size distribution of the fly ash particulates is shown in Figure 2. The distribution is asymmetrical with the modal value of longest dimension being 0.75 microns.

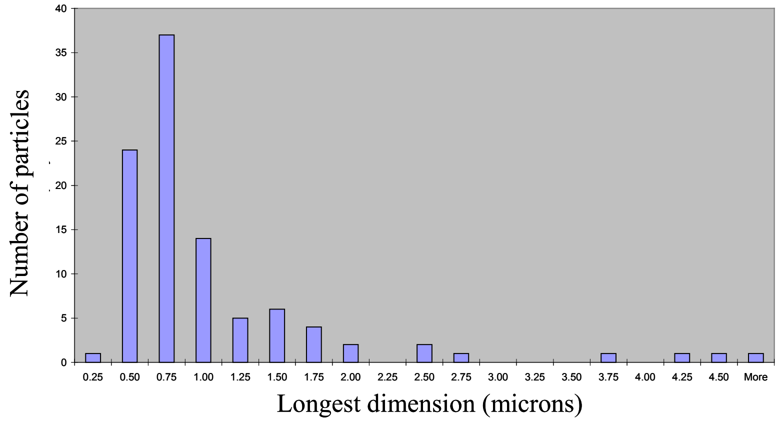


Figure 3 Size distribution of fly-ash particulates

Figure 4 shows the rate of removal of particulates from the sample holder, for a given initial compaction, as a function of distance from the sparks.

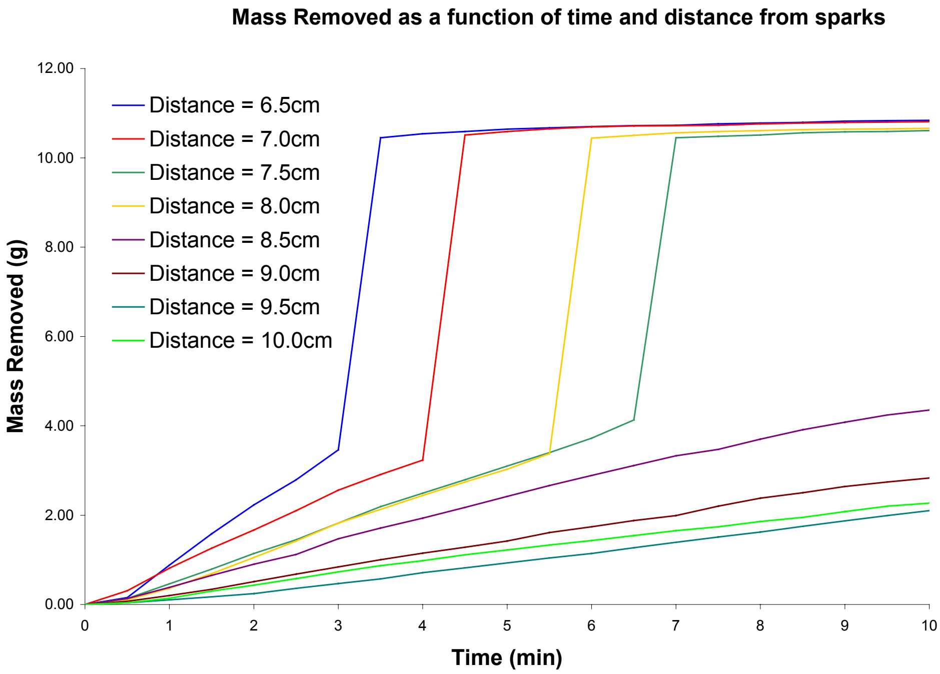
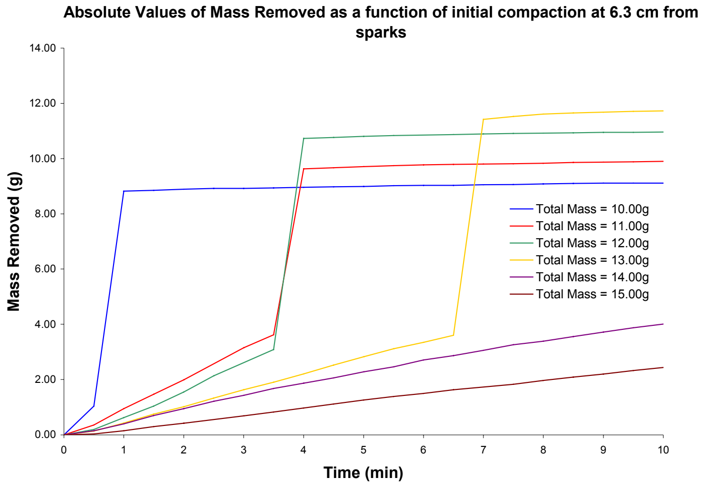


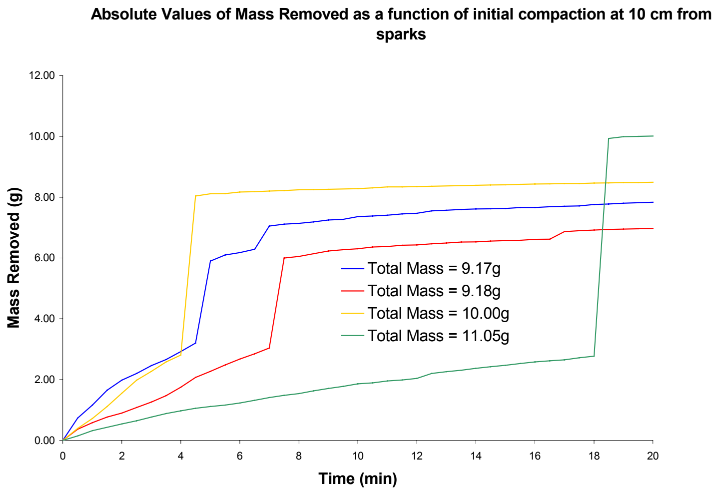
Figure 4 Particulate removal as a function of time and distance of the sample holder from the laser-generated sparks

It is clear that there is a systematic decrease in the rate of removal as the distance increases i.e. the shock intensity decreases. Another noticeable feature is the catastrophic nature of the removal after a certain proportion of particulates have been displaced.

Figure 5 shows the rate at which the particles were removed as a function of time and initial compaction with the sample holder at two different distances from the sparks.



(a)



(b)

Figure 5 Rate of particulate removal as a function of time and initial compaction with sample holder (a) at 6.3 cm and (b) at 10 cm from sparks

Figure 6 shows that for the highest initial compaction, the rate of removal was less at the greater distance (lower shock intensity).

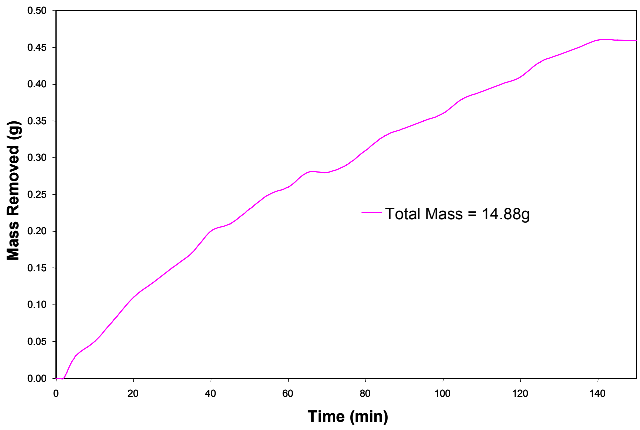


Figure 6 Rate of particulate removal as a function of time with sample holder 10 cm from sparks and with greatest initial compaction.

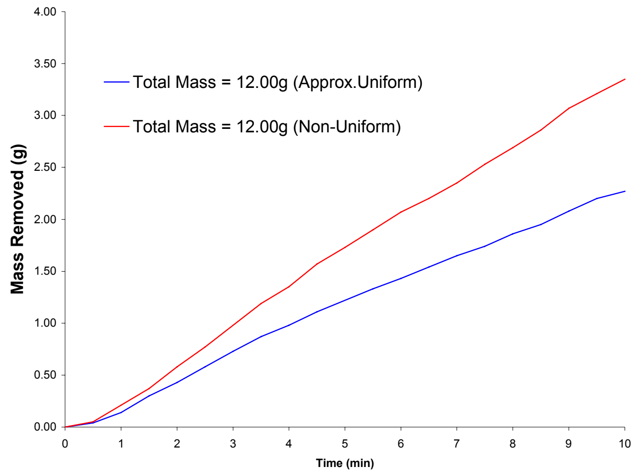


Figure 7 Rate of removal of particles 10 cm from the acoustic shock generation for non-uniform and uniform states of compaction

Figure 7 shows that the rate of particulate removal depends on the uniformity of the initial compaction

2.1.1 Investigation of mechanism of particulate removal

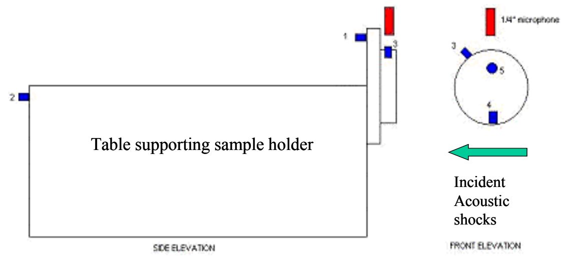


Figure 8 Positions of five acceleration measurements

Shock induced vibrations were measured using accelerometers at five locations: four on the sample holder and one on the supporting table as shown in Figure 8. Resulting accelerations and displacements are shown in Figure 9.

Not surprisingly the greatest induced displacement was at sensor position 1 on the sample holder in the direction of the incident acoustic shocks. However the induced vibration magnitude is rather small: a peak displacement value of less than 2.5 μm.

A mechanical shaker was used to create a similar sinusoidal displacement (Figure 9). However there was no discernible particulate removal with this level of vibration. From this it is concluded that the mechanism of particulate removal is the direct action of the acoustic shocks on the particulates rather than vibration induced in the plate.

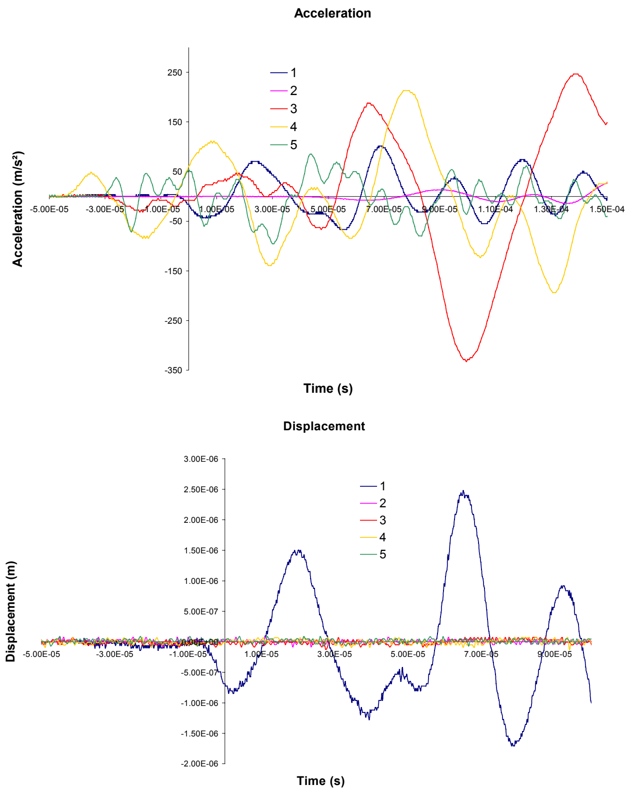


Figure 8 Measured accelerations and displacements induced in the sample holder and supporting structure by the acoustic shocks

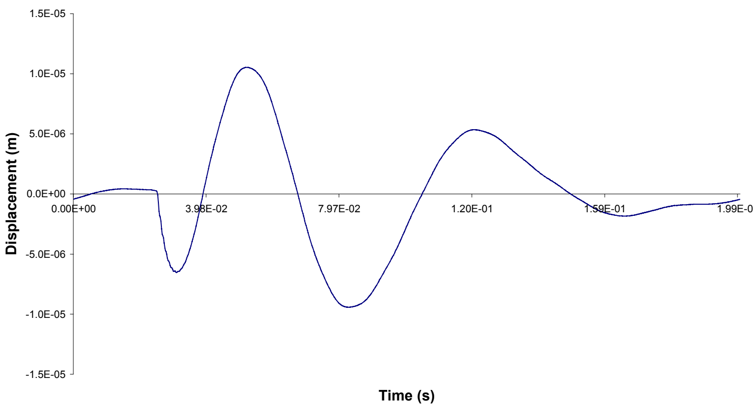


Figure 9 Vibration applied using a mechanical shaker

3 CONCLUSIONS

Removal of particulates compacted on vertical surfaces is achieved by means of laser-generated acoustic shocks with high audio-frequency content. Preliminary experiments have shown that the mechanism involves direct excitation of particles by the shocks rather than induced vibration. The basis has been laid for extending the industrial applications of sonic cleaning using audio-frequency sound.

4 REFERENCES

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