PROPAGATION OF LASER-GENERATED SHOCK WAVES OVER ROUGH SURFACES

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1 INTRODUCTION

Impulsive noise and acoustically-induced ground vibrations from explosions above the ground may cause nuisance. Studies of the propagation of blast sound and acoustically-induced vibration are relatively scarce because controlled field trials with explosions are expensive and difficult. Laboratory simulations of blast sound propagation may make a useful contribution. Acoustic signals from electrical sparks generated by high-capacitance discharge between electrodes have been used extensively for laboratory measurements. Laser-generated sparks are an alternative laboratory source of acoustic shocks. 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. Previous measurements have shown that, at the same source-receiver distance, the peak pressures of the laser-generated sparks are twice as great as those due to electric sparks from electrodes with a 5mm gap. In initial comparisons[1], the standard deviation divided by the average peak sound pressure from 100 laser-generated sparks was found to be less than 3% rather than about 9% for the same number of electrically-generated sparks[1]. At 3 cm from the source the main energy content is near 20 kHz[1]. The frequency content of the laser-generated acoustic shocks decreases and the rise time increases fairly rapidly with range over the first few centimetres as a consequence of air absorption (linear and nonlinear). Peak levels exceeding 140 dB have been measured up to 1.5 m from the source[1]. The main advantages of laser-generated shocks over electrically-produced ones in acoustical experiments are 1) their higher intensity (180 dB peak at 3cm) 2) their superior reproducibility 3) the absence of associated electromagnetic pulses and 4) the flexibility they offer in respect of source position. The laser spark may be located as desired by means of mirrors and has relatively little surrounding equipment; whereas it is difficult to position the electrodes of an electrical spark source with the supporting equipment in as flexible a manner. Previous studies have investigated the fields due to laser-generated acoustic shocks above acoustically-hard surfaces and rough surfaces[1,2]. This paper reports the results of recent experiments in which the propagation of laser-generated shocks has been observed over smooth and rough surfaces. Waveforms and their corresponding spectra are studied. As well as confirming previously reported (linear) influences of surface roughness on waveform duration and rise time[1], these recent data indicate that surface roughness enhances higher harmonics associated with non-linear effects.

2 MEASUREMENT SYSTEM

2.1 Laser-generated shocks

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. A convex lens with focal length of 10 cm has been 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. The sensing and analysis system for the rough surface measurements consisted of high-pressure level high frequency microphone B&K Type 4138 (1/8″), a conditioning amplifier, B&K Type 2636; an NI 5911 data acquisition card enabling sampling rates as high as 100 million samples per second and LabView software.

2.2 Surfaces

A 6mm thick glass plate of dimensions 76m × 76m was used to provide a smooth rigid surface. Various 'hard' rough surfaces were formed by placing either 1 – 3 mm or 3 – 8 mm sand grains (the ranges given are of the maximum grain dimensions) in random patterns and with different packing densities on the glass plate. The maximum dimensions of the largest grains (8mm) are small compared with the wavelength (1.7 cm) at the frequency of the peak laser-generated shock energy near the spark (20 kHz). The arrangement of laser, lens and microphone are shown in Fig. 1.

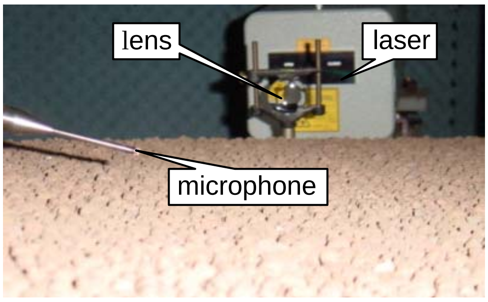

Figure 1 Laser, lens and microphone arrangement for measurements close to a rough surface.

3 RESULTS

Figures 2(a) - 2(d) shows example mean waveforms obtained from 100 pulses at each location and Figures 3(a) - 3(d) show corresponding spectra obtained from these mean waveforms at horizontal distances of 0.06 and 0.2m from the source over smooth and rough (3 - 8 mm grain) surfaces respectively.

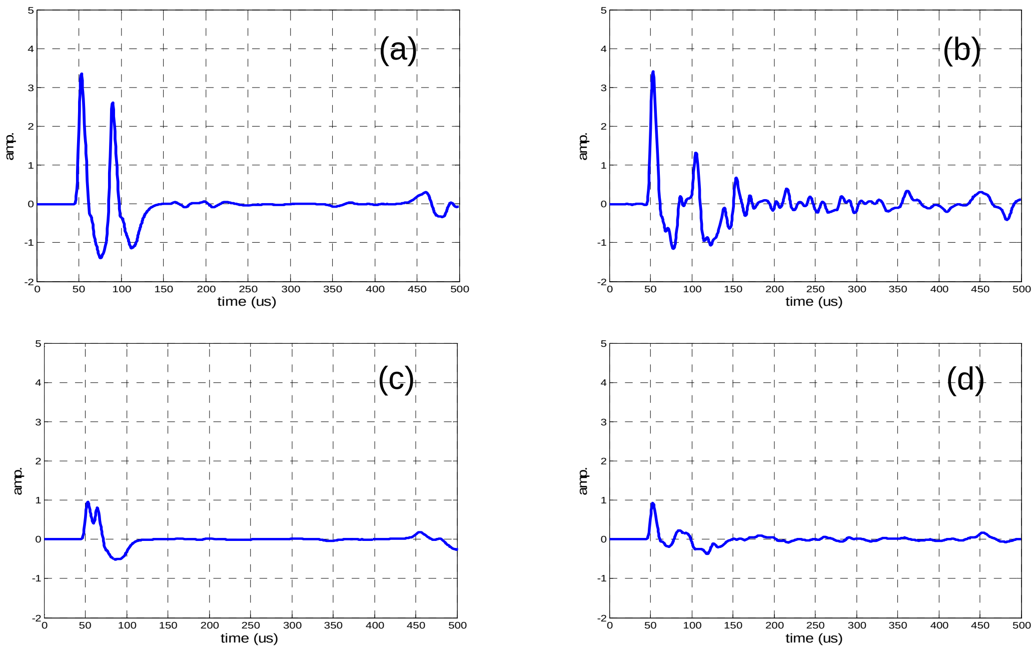

Figure 2 Example laser-generated shock waveforms obtained at 0.06m ((a) and (b)) and 0.2m ((c) and (d)) from the source over smooth ((a) and (c)) and 3 – 8 mm grain rough ((b) and (d)) surfaces with source height 0.025m and receiver height 0.02m.

The second peaks in the waveforms (Figure 2) corresponding to specular reflections over the smooth surface are considerably reduced in magnitude and slightly delayed over the rough surface. The tails of the waveforms over the rough surface are much more oscillatory than those of the waveforms recorded over the smooth surface. Indeed, over the rough surface (Figures 2(b) and (d)), there is evidence of a secondary waveform travelling at a slower speed than the primary arrival.

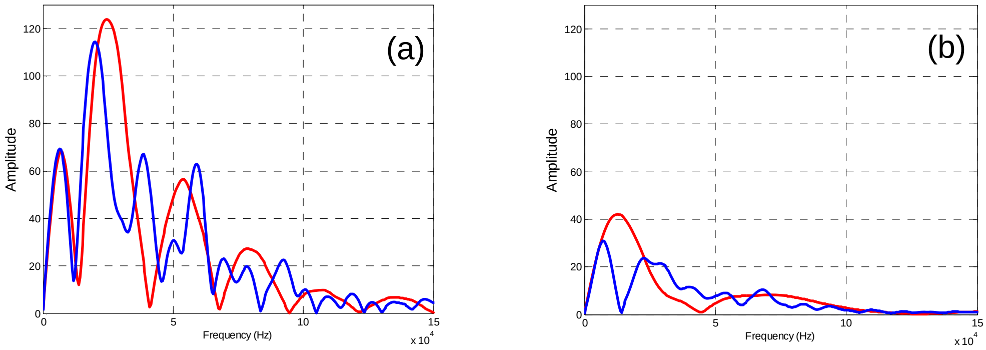

Figure 3 Spectra corresponding to the mean waveforms shown in Figure 2 for source-receiver separations of (a) 0.06m and (b) 0.2m over smooth (red curves) and rough (blue curves).

At the shorter source-receiver separation over both the smooth and rough surfaces the spectra contain several higher harmonics and a sub-harmonic (Figure 3(a)) which result from the non-linearity of the shocks. Of particular interest at 0.2m source-receiver separation, is that, whereas the higher harmonic contributions have been reduced over the smooth surface, over the rough surface there is a reduction and shift in the first peak to lower frequency and relatively persistent high frequency component near 35 kHz. Figure 4 shows that, at 0.2m horizontal source-receiver separation, as the receiver height above the rough surface is increased from 0.01m to 0.035m, the relative contribution of the higher frequency peak increases.

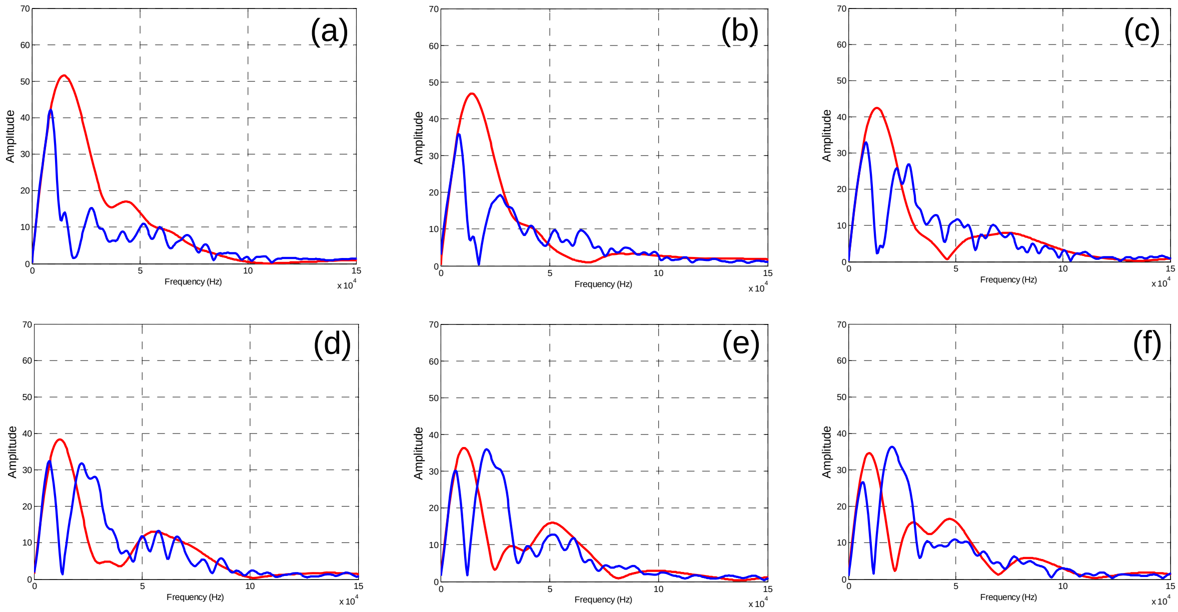

Figure 4 Variation of shock spectra at 0.2m horizontal range as the height of the receiver is raised: (a) 0.01m (b) 0.015m (c) 0.02m (d) 0.025m (e) 0.03m and (f) 0.035m. The source is fixed at 0.025m height.

Figure 5 shows results obtained over the smooth surface at 0.2m range, with source height at 0.025m and receiver at heights between 0.01m and 0.03m. At the lowest receiver height the direct and reflected arrivals overlap thus giving a higher first peak. As the receiver height is raised the direct and reflected arrivals separate. However the amplitude of the peak corresponding to the direct arrival is not changed much by the change in geometry since the direct path length does not change much.

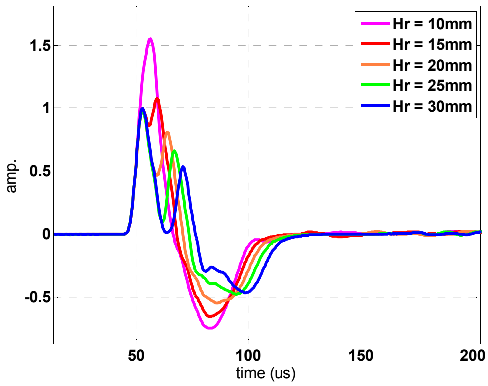

Figure 5 Waveforms recorded over the smooth hard surface with source height at 0.025m and receiver, at a horizontal range of 0.2m, with heights between 0.01m and 0.03m.

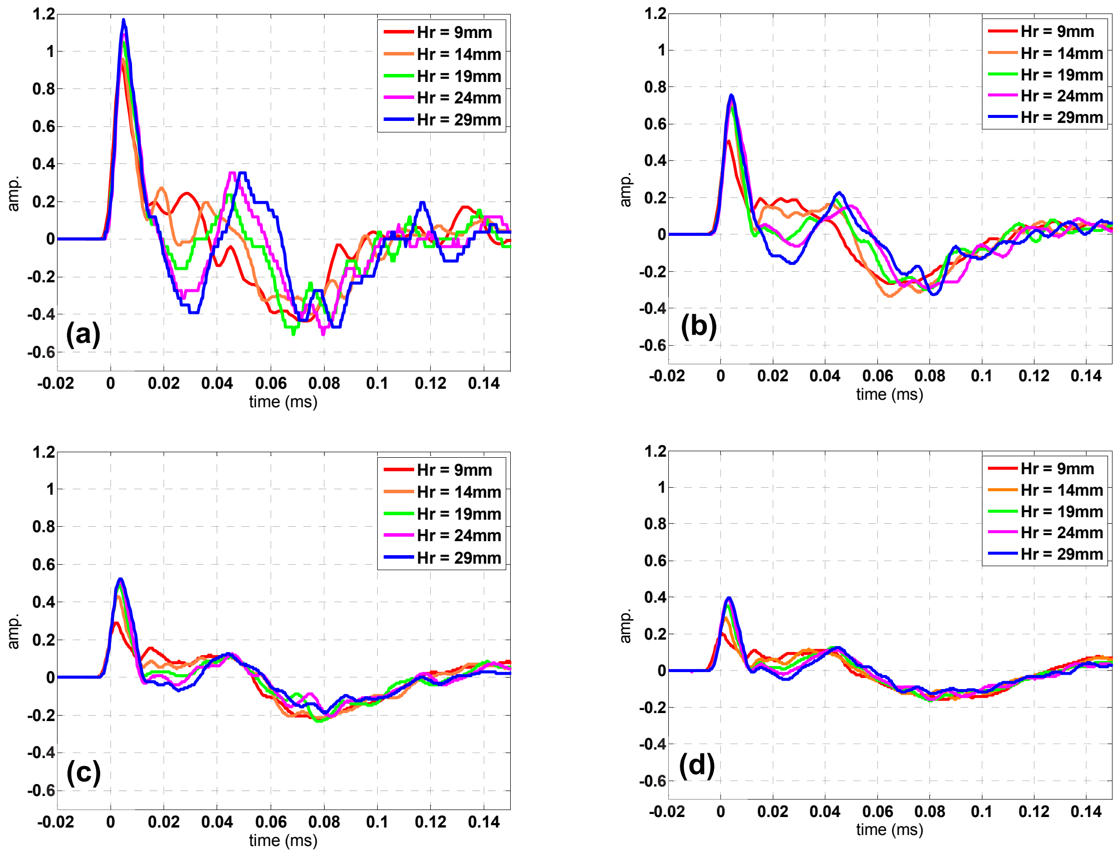

Figure 6 Acoustic waveforms measured at source and receiver heights between 0.009 m and 0.029 m and ranges of (a) 0.2 m (b) 0.3 m (c) 0.4 m and (d) 0.5 m over the rough surface formed by 3 – 8 mm sand grains packed to a uniform density of 110,000 grains per m^2.

Figure 6 shows waveforms obtained with the source at a height of 0.03m and the receiver at heights between 0.009 m and 0.029 m and ranges between 0.2 m and 0.5 m over a rough surface formed by distributing a fairly dense packing (110,000 grains per m^2) of sand grains with maximum dimensions of between 3 and 8 mm on the glass plate surface. In contrast to the smooth surface waveforms (Figure 5), the amplitudes of the first peaks corresponding to the main arrivals, increase as the receiver height increases. From other data (e.g. Figure 2) it is known that the specularly-reflected arrival is much reduced by the surface roughness. So this phenomenon must be another consequence of the higher harmonic enhancement remarked in Figure 4. This conjecture is confirmed by Figure 7 which shows the spectra corresponding to the waveforms in Figure 6. As in Figure 4, the relative contribution of the roughness-induced higher frequency peak increases with receiver height.

As well as reducing the amplitude of the direct arrival, the rough surface causes formation of a secondary wave with a low frequency tail. For the 9mm and 14mm receiver heights, the initiation of this wave is merged with the reduced specular reflection at 0.2 m range (Figure 6 (a)) but is more distinguishable at ranges between 0.3 m and 0.5 m (Figures 6(c) and 6(d)) where it replaces the rarefactions associated with the equivalent arrivals over a smooth surface. The initial amplitudes of the secondary arrivals decay rapidly with increasing receiver height above the surface, which is consistent with surface wave behaviour. The amplitude of the initial part of the secondary arrival decays less rapidly with distance than the main arrival which is also consistent with surface wave behaviour. The initial part of the secondary wave travels at approximately the speed of sound in air which is calculated as 342 m/s.

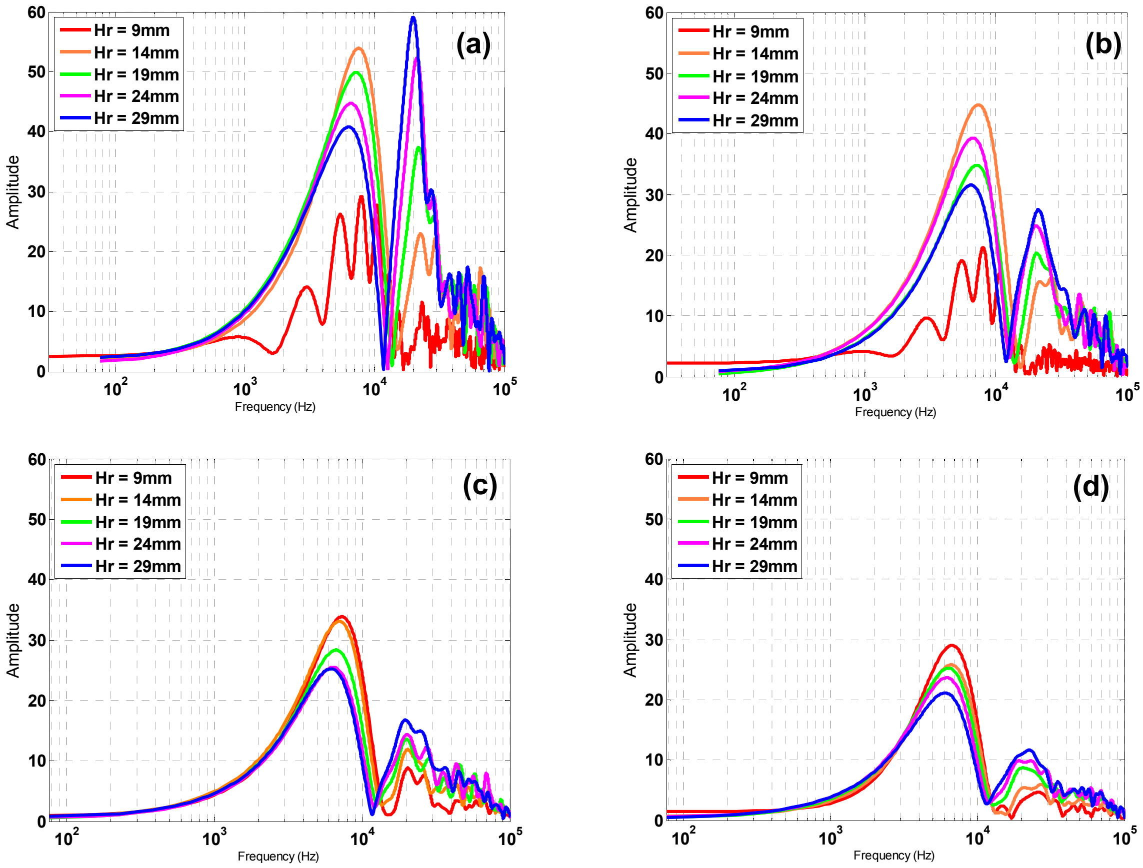

Figure 7 Spectra measured at heights between 0.009 m and 0.029 m and ranges of (a) 0.2 m (b) 0.3 m (c) 0.4 m and (d) 0.5 m over the rough surface formed by 3 – 8 mm sand grains packed to a uniform density of 110,000 grains per m^2. The source height is fixed at 0.03m.

The influence of surface roughness may be investigated with respect to either free field data or data obtained over a hard smooth surface. Figure 8 shows excess attenuation spectra (level with respect to free field) obtained over (a) the smooth rigid surface, (b) 1 – 3 mm grain rough surface and (c) 3 – 8 mm grain rough surface with a source height of 0.025m, a receiver height of 0.02m and source-receiver separations of (a) 0.4m, (b) 0.2 – 0.5m and (c) 0.4m.The frequency of the main 'ground effect' destructive interference dip is changed from 56 kHz over the smooth surface to 21 kHz over a rough surface of 1 – 3 mm grains and to 10.3 kHz over a rough surface of 3 – 8 mm grains at comparable packing density and source-receiver separation. Figure 7(b) shows that the rough surface 'ground effect' dip is almost independent of range between 0.2 and 0.5m near grazing incidence.

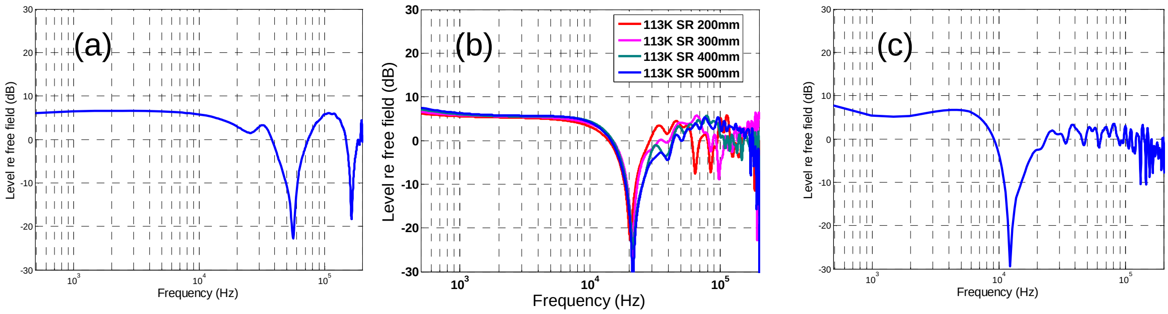

Figure 8 Excess attenuation spectra obtained over smooth and rough surfaces with source height of 0.025m and receiver height of 0.02m: (a) over a smooth surface with source-receiver separation 0.4m (b) over a 1 – 3 mm grain rough surface at a packing density of 113,287 grains per m^2 and source-receiver separations between 0.2m and 0.5m and (c) over a 3 – 8 mm grain rough surface at a packing density of 110,000 grains per m^2 and source-receiver separation 0.4m.

Figure 9 shows equivalent results to Figures 8(a) and (c) but with respect to the sound fields over the smooth surface. The increased contributions of nonlinear harmonics due to the rough surface show as peaks in the level relative to a (smooth) hard surface at frequencies higher than those of the main 'ground effect' dip.

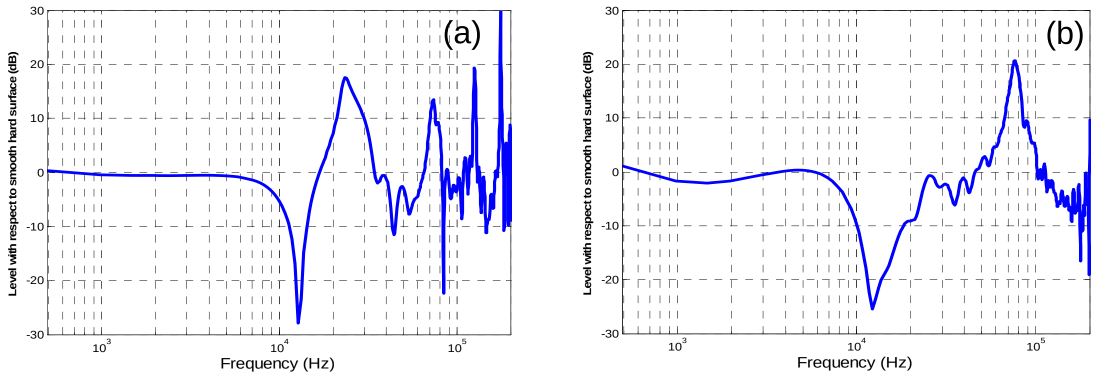

Figure 9 Ratios of spectra obtained over a 3 – 8mm granular rough surface and over a smooth surface with source height of 0.025m, receiver height of 0.02m and source-receiver separation of (a) 0.2m and (b) 0.5m.

The reduction in the frequency of 'ground effect dip' by the rough surfaces may be interpreted as the result of a roughness-induced 'effective' impedance as reported elsewhere[3,4]. The impedance spectra, and the excess attenuation spectra from which they may be deduced[5], depend on roughness size (compare Figures 8(b) and 8(c)) and packing density. The dependence on packing density is demonstrated in Figures 10(a) and 10(b).

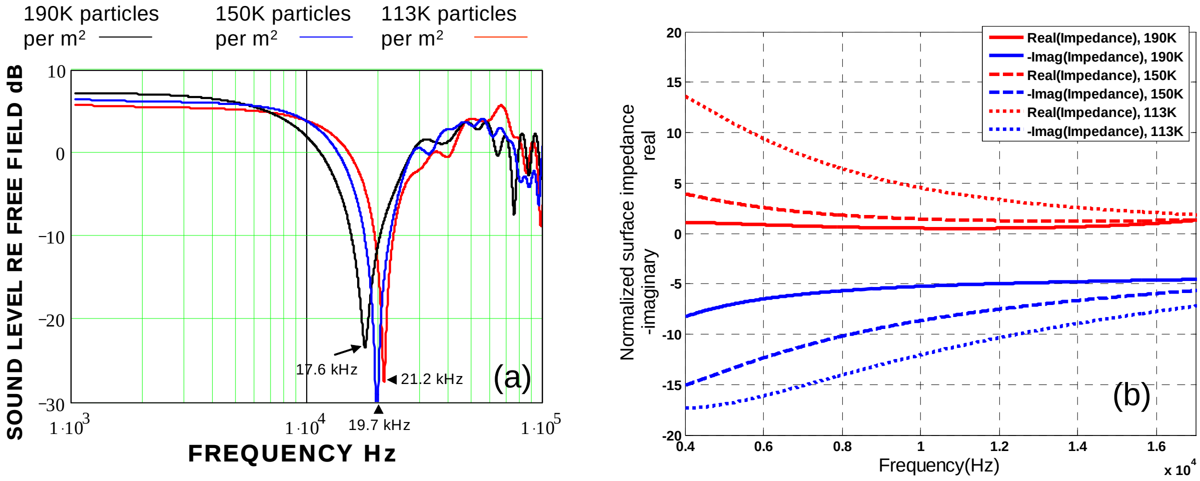

Figure 10 (a) Measured excess attenuation spectra obtained with source and receiver heights of 0.025m and 0.02 m separated by 300mm over different packing densities of 1 – 3 mm grains (b) effective impedance spectra deduced from the EA spectra.

4 CONCLUSIONS

Laboratory simulations of blast sound propagation using laser-generated acoustic shocks are useful adjuncts to field experiments. In a series of measurements over rough surfaces in the laboratory it has been demonstrated for the first time, to the authors' knowledge, that as well as the expected (linear) effects on pulse duration, rise time and excess attenuation, surface roughness enhances the contributions from nonlinear harmonics compared with a smooth surface. This has potential implications for the propagation of acoustic shocks outdoors and predictions of the nuisance associated with firing ranges.

Further work will explore the origin of the phenomenon of roughness-induced nonlinear harmonic enhancement and the feasibility of using surface roughness to control acoustic shock propagation.

5 REFERENCES

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