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USE OF ACOUSTIC SHOCK WAVES FROM FOCUSED LASER BEAMS FOR STUDIES OF SURFACE ACOUSTICS

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1 INTRODUCTION

Although the use of pulsed lasers to generate acoustic pulses in both solid and liquid media is well known [1,2], research into laser-generated acoustic pulses in air has not been reported to the same extent. Laser users usually try to avoid air breakdown in air, since the laser energy is absorbed and heat is produced when charged particles such as electrons stripped from atoms are generated[3]. Nevertheless it remains a fact that strong sparks can be produced in air when a light intensity, of the order of 10^{11} W cm^{-2}, is applied to a small volume. This requires that the light beam from a laser has a peak power of the order of 10 MW or more and that this beam is focused through a lens. In the focal area, the air absorbs energy from the light by means of the cascade process. The energy gain causes local heating of the gas, which expands outwards as a propagating shock wave with a rarefaction or suction region behind the shock front. Thus a powerful acoustic source is produced in air and it can be located so as to avoid unwanted reflections from the associated equipment. Given the similarity between the laser-induced acoustic shock waveform and that associated with a blast wave[4], acoustic pulses associated with laser-induced sparks could be used to simulate blast sounds from explosions or sonic booms in the laboratory and to investigate the associated propagation effects. Measurements made near the laser sparks show that the free field sound pressures obtained within a source-receiver distance of less than 1.5 m are at levels sufficient to result in nonlinear effects. Therefore, laser-generated acoustic shocks can be used for laboratory-based research into nonlinear acoustics.

2 Apparatus

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. The gas breakdown induced by the laser has a duration of between 4 and 6 nanoseconds[5]. The power *P* in a pulse with duration *T* and energy *E* is

$$P = \frac{E}{T} \tag{1}$$

The intensity *I* in area *S* is

$$I = \frac{P}{S} \ . \tag{2}$$

If the duration of the pulse is between 4 and 6 nanoseconds, the pulse power of the III-10 Nd: YAG laser at 1064 nm wavelength is between 133 and 200 MW.

Without focussing, the laser beam has a beam diameter of 9 mm and the intensity of the laser pulse is between 2.07 and 3.14 $\times 10^8$ Wcm^{-2}. This intensity is much lower than the threshold of 10^{11} Wcm^{-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 and 2.83 Wcm^{-2}. In the experiments reported here, the laser beam was focused using a lens with a focal length of 10cm.

The sensing and analysis system that was used for measurements of laser-induced acoustic shock waves consisted of microphones of B&K Types 4138 (1/8″) and 4939 (1/4″); a high frequency amplifier, B&K Type 2636, an NI 5911 data acquisition card and LabView software. The rise time, the peak pressure, duration and stability of the laser-induced acoustic shocks have been investigated.

3 CHARACTERISTICS OF THE LASER-INDUCED ACOUSTIC SHOCKS

A measured waveform at 3cm from the spark source, using a 1/8″ microphone, is shown in Fig 1. The peak pressure at this distance is found to be 181dB re 20 μPa (22,683 Pa). Such a high sound pressure level cannot be generated by conventional laboratory point sources, such as a point source loud speaker or an electric spark. Since nonlinear convective effects, in contrast with dissipative effects (such as viscosity and thermal conductivity), become apparent at sound pressure levels of around 140 dB[4], the measured laser-induced spark source is useful for research into non-linear acoustics. Even at a source-receiver distance of 150cm, the peak pressure of the received pulse is higher than 140 dB. As shown by the sound spectrum in Fig.1, the laser-induced acoustic shock is broadband and high frequency. The sound energy lies between 3 kHz and 150 kHz with a peak at 20 kHz.

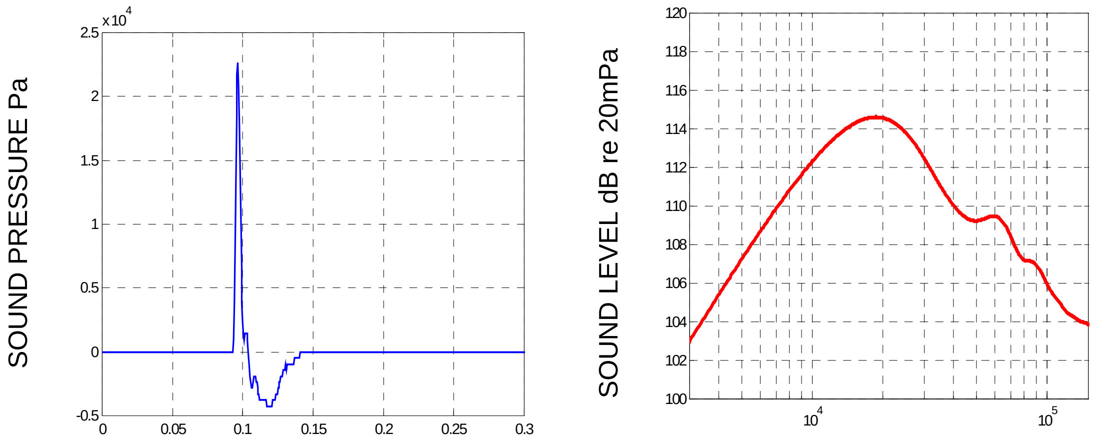
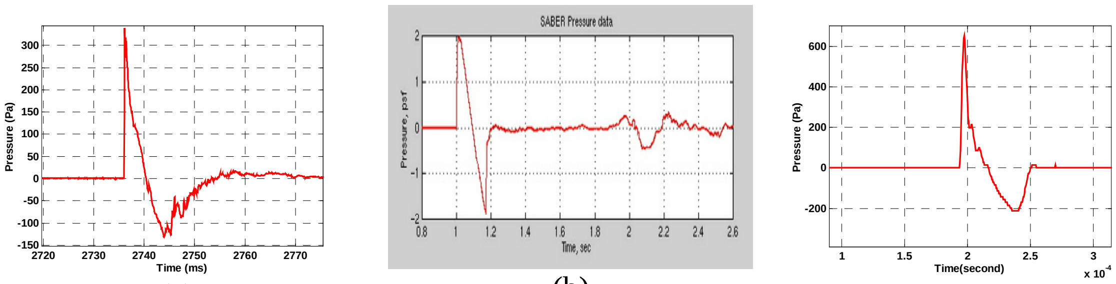


Figure 1: (a) Measured laser-generated acoustic pulse waveform and (b) corresponding spectrum at a source-receiver distance of 3 cm: (a) The peak pressure is 181dB (22,683 Pa), the duration is 48 μs, the positive duration is 12 μs and the rise time is 3.5 μs; (b) The corresponding spectrum is high frequency and broad band with main energy content near 20KHz.

One of potential uses of the laser-induced acoustic shocks is to simulate sound from explosions and sonic booms in the laboratory. The blast waveform at 100m from a 0.1425 kg C4 explosion (Fig. 2a) may be compared with the signal received by an 1/8″ microphone due to the laser-induced acoustic shock received at 60cm from generation point (Fig. 2c). The waveform shapes are rather similar but have different duration associated with the very different frequency content. Fig. 2b shows a sonic boom waveform measured on the ground during a supersonic flight. Clearly, the waveform of the laser-generated shock wave only resembles the N-wave of a sonic boom during the positive pressure phase, but with a rather smaller wavelength. Nevertheless, since the positive peak pressures and the rise times are the scaling quantities of interest for simulating sonic booms in the laboratory, the laser-generated waveforms are satisfactory for scale modelling of sonic boom propagation also. Moreover recent measurements using a baffle to reduce effects of diffraction by the microphone have resulted in waveforms closer to the required N-wave shape[13].



(a) (b) (c)

Figure 2: (a) Blast wave measured at 1m height and 100m horizontal distance from the detonation of 0.1425 kg of C4 at 2m height above sandy soil (b) A sonic boom measured at the ground generated by a SR-71 aircraft moving at Mach 1.27 and at 9300m height; (c) a laser-generated acoustic pulse at 60 cm from the source.

The peak pressures due to the laser-generated shocks are shown as a function of source-receiver distance in Fig. 3. The decay with distance becomes logarithmic beyond about 10 cm from the source. Fig. 3 shows that there increasing departure from inverse square law with distance. In part this is associated with air absorption. The air absorption coefficient α has been calculated using equations in the references[6, 7, 8] and Figure 3 shows the effect of air absorption on the peak pressure of the laser spark as the source-receiver distance is changed from 3cm to 153cm is 1.57 dB. The expected reduction from spherical wavefront spreading over this distance is 34.15 dB. The measured reduction from 3cm to 150cm is 40.92 dB. So after allowing for air absorption effects, there is discrepancy of more than 5 dB.

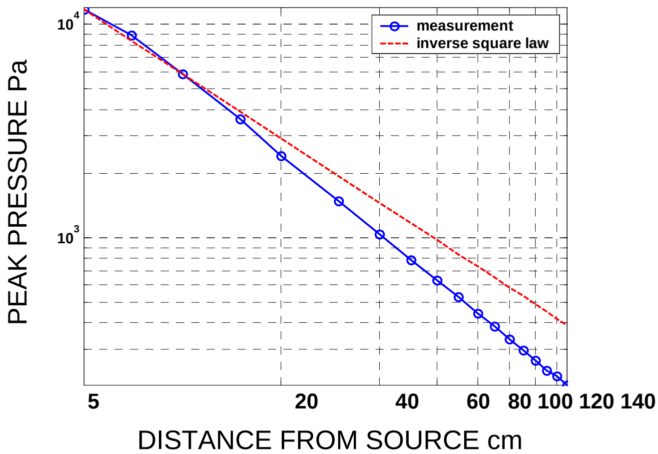


Figure 3: The peak pressures due to the laser-generated shocks as a function of source-receiver distance from 3cm to 150cm measured using a 1/8″ microphone

Estimates of hydrodynamic nonlinear effects in air may be made by approximating the laser-generated pulses as triangular waveforms. The changes with distance x of the amplitude p and duration T of a triangular pulse are described by the following expressions[9].

$$p = \frac{p_0}{\sqrt{1+\dfrac{\varepsilon p_0 x}{c_0^3 \rho_0 T_0}}}, \qquad (3)$$

$$T = T_0\sqrt{1+\frac{\varepsilon p_0 x}{c_0^3 \rho_0 T_0}}, \qquad (4)$$

where $p_0 = p(x=0)$, $T_0 = T(x=0)$, , ρ_0 is the density of air, c_0 is adiabatic sound speed in air, $\varepsilon = \frac{\gamma+1}{2} \approx 1.2$ and γ is the adiabatic constant.

Using equations (3) and (4), a peak pressure of 22.163 KPa, and assuming a duration (t_0) of either 12μs (the positive duration) or 48μs (the total duration) which are the measured characteristics of the waveform at 0.03m from the spark, the predictions shown in Figures 4a and 4b are obtained as a function of distance from the source. Fig.4a suggests a difference between spherical spreading and levels after allowing for hydrodynamic nonlinearity of between 3.5 and 7.8 dB. In particular, for the given peak pressure, a reduction due to hydrodynamic nonlinearity in air of 5.2 dB is predicted to correspond to a (triangular) pulse duration of 26μs at 3cm from the spark. From the data and calculations in Figures 3 and 4a it may be concluded that, although the spark itself is asymmetric and elongated in the direction of the incoming light beam[10], the associated acoustic pulse behaves essentially as though from a point source at distances beyond 10 cm but with additional nonlinear hydrodynamic losses and air absorption. Fig.4b shows that hydrodynamic nonlinearity in air is predicted also to cause gradual elongation of the pulse with distance resulting in an increased duration at a distance of 1.5m from the spark of between 150% and 250% of that at 3cm from the spark.

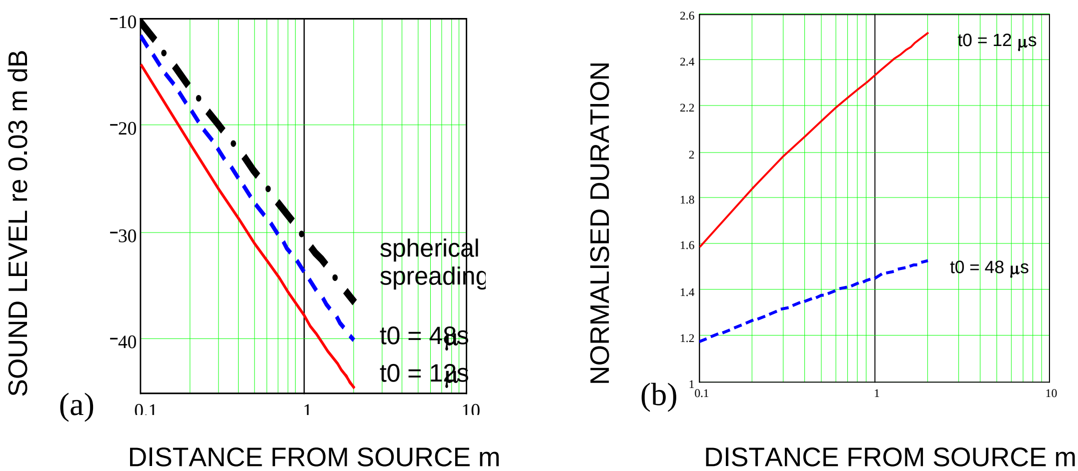


Figure 4: (a) Predicted effects of hydrodynamic nonlinearity in air on peak pressure as a function of distance assuming triangular waveforms and pulse durations of either 12 μs or 48 μs (b) Predicted effects of hydrodynamic nonlinearity in air on pulse duration as a function of distance; parameters as for (a)

The peak pressures in 50 shocks have been measured at 14 source-receiver distances between 20cm and 150cm. The results from using both 1/8″ and ¼″ microphones are shown in Fig. 5a and 5b. The difference between the 1/8″ receiving system and the ¼″ receiving system is the frequency response i.e. up to 200KHz for the 1/8″ microphone but only up to 100 KHz for the ¼″ microphone. Consequently, the use of a 1/4″ microphone results in lower peak pressures and less apparent absorption but preserves the overall trend of the variation with distance. The error bars represent the standard deviations of the measured peak pressures. The standard deviations are found to vary between only 1.5% and 3.0% of the peak pressures in Fig. 5a, which indicates that the laser-induced acoustic pulses are very repeatable. The repeatability of the laser-generated acoustic shocks is quite useful for the measurements over a rough surface described in the next section.

4 PROPAGATION OVER ROUGH HARD SURFACES

A schematic of the system that has been used for laboratory measurements of the propagation of laser-generated acoustic shocks is shown in Fig.6. Measurements have been carried out using a ¼″

microphone over six different rigid rough surfaces consisting of single layers of randomly-distributed but uniformly-sized grains fixed to smooth glass plates. The grains were fixed to the glass base by epoxy adhesive. The grains, the glass base plate and the dried epoxy adhesive are acoustically rigid. The grain sizes on the six rough surfaces varied between 0.2mm and 5.0mm i.e. between 1/65 and 1/3 of the wavelength at the peak energy frequency (20KHz).

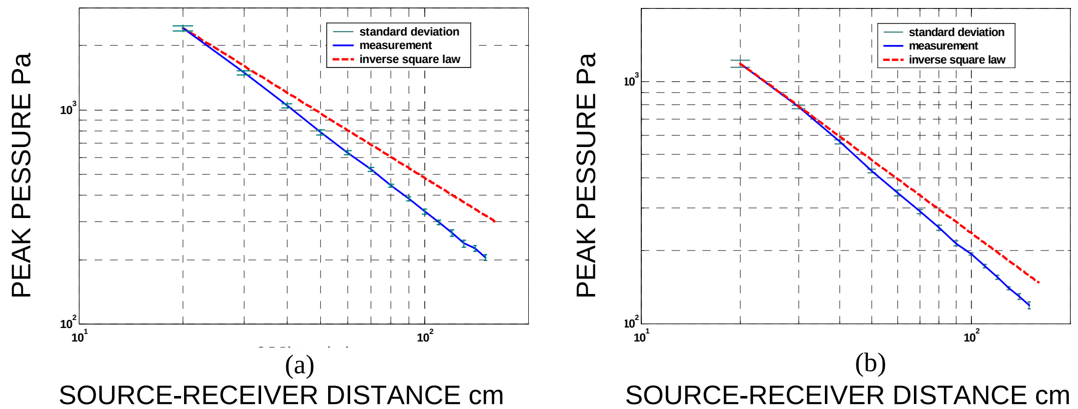


Figure 5: (a) Comparison between the measured (1/8″ mic) peak pressures as a function of distance from the source and levels expected as a result of spherical spreading only; (b): Comparison between the measured (1/4″ mic) peak pressures as a function of distance from the source and levels expected from spherical spreading only.

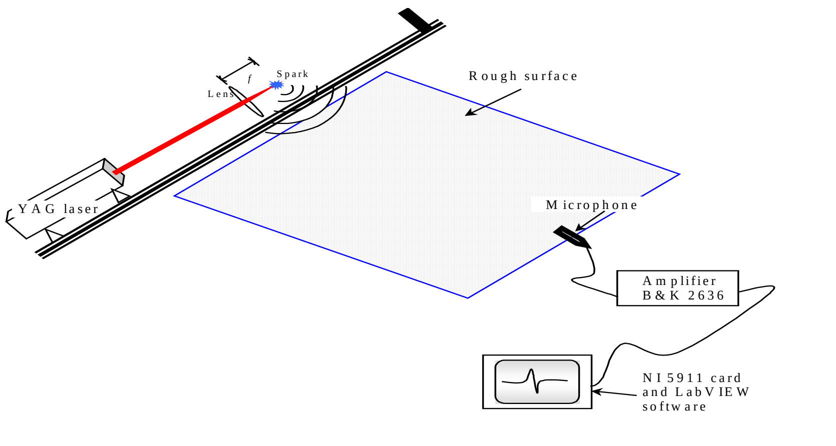
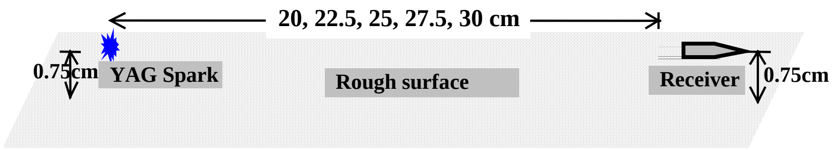
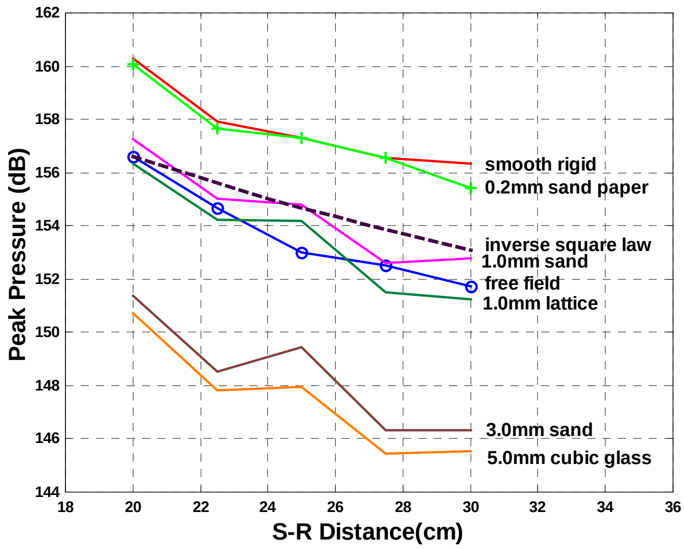


Figure 6: Schematic of laser-generated acoustic pulse measurements.

The distances between the source and the receiver were set at 20.0, 22.5, 25.0, 27.5, and 30.0cm respectively. The source and the receiver heights were kept constant at 0.75cm, corresponding to grazing angles of 4.29, 3.81, 3.43, 3.12, and 2.86 degrees respectively (see Fig.7a). The data in Fig.7b show a large variation in the measured sound peak pressures at the same source receiver distance as a function of the surface roughness. The difference in peak pressure over the smooth rigid surface and the 5mm cubic glass grain surface was found to be as much as 1,400Pa (9.4dB level difference) at 20 cm from the laser spark source (see Fig.7b). Over the range of surface roughness used, the sound attenuation at a given distance was found to increase with increasing roughness size. For the data shown, the path length differences between the direct and the scattered signals of the geometry of the measurements are between 0.056 and 0.037cm. This implies time delays of between 1.6 and 1.1μs at the receiver points. These time differences are less than 2% of the pulse duration, which is between 64.5 and 108.0 μs, as shown in Table 1 and may account for the interference effects observed in Fig.7b. Without the ground surface, the peak pressures decreases monotonically with increasing distance, as shown by the free field curve in Fig. 7b.





(b)

Figure 7 (a): Schematic of the measurements over rough surfaces. (b) Measured peak pressures (dB) as a function of distance in free field, over a smooth acoustically rigid surface and over 5 different rough surfaces. Inverse square law decay is shown also.

The data in Fig.8 show the measured sound energy levels at the same source receiver distance (receiver height 15mm) as a function of the surface roughness. The sound attenuation at a given distance was found to increase with increasing roughness size.

Table 1 presents data at a source-receiver distance of 30cm. The peak pressures, rise times, the peak-to-peak times, and the duration given in the table are the average values for 50 laser-induced pulses. The data in Table 1 indicate that the waveform is elongated during propagation over rough surfaces. For example, at 30cm from the source over a rough surface formed with 5mm cubic glass, the measured duration of the laser-generated acoustic shock is increased from 64.5μs over a smooth rigid surface (compared with a free field duration of 48μs at 3 cm from the source) to 108μs. Thus it is demonstrated that surface roughness causes acoustic shock waveform in addition to that due to hydrodynamic nonlinearity in air (see Fig.4b). Fig.9 compares waveforms received at 30cm range over smooth and rough (5mm cubic glass) surfaces. Apart from the significant reduction in peak pressure and the elongation, the waveform recorded over the rough surface shows evidence of a surface wave creation similar to that observed in (linear) pulse experiments[11].

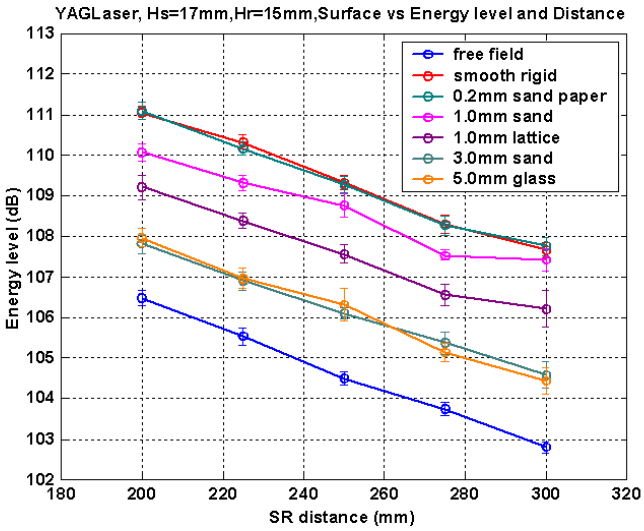


Figure 8 Measured energy level (dB) as a function of distance in free field, over a smooth acoustically rigid surface and over 5 different rough surfaces. The definition of 'Energy level (dB)' at receivers is: $EnergyLevel = 10\log\left[\left(\int_0^{200\mu s} p^2(t)dt\right)/\left(p_0{}^2 \times 1second\right)\right]$ (dB),

p_0 = 2 x 10^{-5} Pa;

Table 1. Average data from 50 pulse measurements at SR = 30cm, Hs = 0.75cm, Hr = 0.75cm

No	Description	Grain size (mm)	$P_{max}(Pa)$ *at 30 cm*	T_{rise} (μs)	T_{p-p} (μs)	T_{Dura} (μs)
1	Free field		771	6.0	32.0	60.5
2	Smooth rigid surface		1314	5.5	40.5	64.5
3	P80D sand paper	0.2 mm	1174	7.5	37.0	77.0
4	Sand paper 14/25 grade surface	1.0 mm	871	12.5	37.5	82.5
5	Sanding lattice (9089NA)	1.0 mm	731	14.5	34.5	83.5
6	Rough gravel (LATERLITE LECA 2~3 mm)	3.0 mm	413	23.5	41.0	92.5
7	Rough glass surface (Cubic glass size ≈5mm)	5.0 mm	378	29.0	48.0	108.0

P_{max} : Positive peak pressure; T_{rise} : Rise time; T_{Dura} : (total) Duration of impulse

T_{p-p} : Peak-to-Peak duration i.e. the time interval between positive and negative peaks

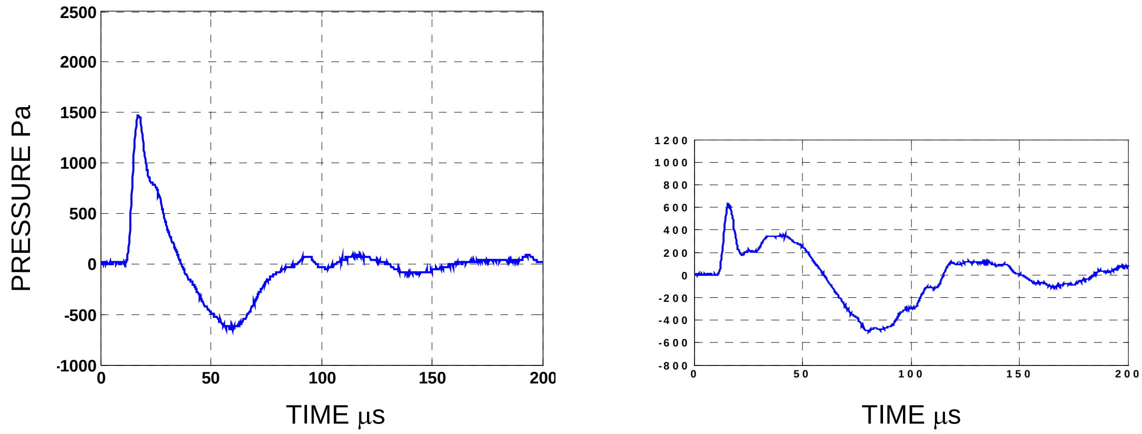


Figure 9: Comparison of measured waveforms at 20 cm (a) over a smooth glass surface (b) over a rough surface (5mm cubic glass) with the spark source at 1.7cm height and microphone at 1.5cm height.

5 CONCLUSIONS

The acoustical characteristics of pulses associated with air breakdown caused by a focused pulsed laser beam has been investigated. The peak pressure of the laser generated sound source in air can be as high as 181dB (re 20µPa), which is useful for research into nonlinear acoustic effects. By using the laser-generated sound, the propagation of explosions and sonic booms can be simulated conveniently in the laboratory. Small-scale measurements made over a series of ground surfaces have shown that the propagation of laser-induced acoustic shocks near to the ground is sensitive to small-scale ground roughness.

7 ACKNOWLEDGEMENTS

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