Aspects of laser-generated acoustic shock waves in air

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Introduction

Although the use of pulsed lasers to generate acoustic pulses in both solid and liquid media is well known, research into laser-generated acoustic pulses in air has not been reported to the same extent. Laser users usually try to avoid a breakdown in air, since the laser energy is absorbed and heat is produced when charged particles such as electrons stripped from atoms are generated. 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, 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 1.5m are at levels sufficient to result in nonlinear effects and are highly repeatable. Therefore, laser-generated acoustic shocks can be used for laboratory-based research into nonlinear acoustics. Results of laboratory measurements illustrating the effects of surface roughness on nonlinear propagation are presented here. The high-frequency content and high-amplitudes of laser-generated acoustic shocks makes them useful also for measurements of acoustic transmission through porous materials. Preliminary results of measurements on three materials are presented here.

Laser and Measurement System

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. 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 focusing, the laser beam has a beam diameter of 9 mm and the intensity of the laser pulse is between 2.07 and 3.14 x 10^10 W cm^-2. This intensity is much lower than the threshold of 10^12 W cm^-2 required to break down the air. In the experiments reported here, the laser beam was focused using a convex lens with a focal length of 10cm 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 W cm^-2. The sensing and analysis system that was used for measurements of laser-induced acoustic shock waves consisted of high-pressure and high frequency microphones, B&K Types 4138 (1/8″) and 4939 (1/4″); a high frequency amplifier, B&K Type 2636, a National Instruments 5911 data acquisition card and LabView software. The peak pressure, duration and stability of the laser-induced acoustic shocks have been investigated.

Characteristics of the laser-induced acoustic shocks

A measured waveform at 3 cm from the spark source, using a 1/8″ microphone, is shown in Figure 1(a). The peak pressure at 1.88 and 2.83 W cm^-2 ranges from about 0.3mm so that the light intensity in the focused spot is between 1.88 and 2.83 W cm^-2. The peak pressure, duration and stability of the laser-induced acoustic shocks have been investigated.

The peak pressures due to the laser-generated shocks measured with 1/8″ microphone are shown as a function of source-receiver distance in Figure 2. The decay with distance becomes logarithmic beyond about 10 cm from the source. Figure 2 shows that there is increasing departure from inverse square law with distance. This is associated with air absorption and with nonlinear hydrodynamic loss in air. As the source-receiver distance increases from 3 cm to 153 cm the peak pressure of the received pulse is higher than 140 dB. The spectrum of the laser-induced acoustic shock is broadband and high frequency (Figure 1(b)). The sound energy spectrum is between 3 kHz and 150 kHz and peaks at 20 kHz.

The peak pressure is given by the following equation:

\[ p = \frac{p_0}{1 + \frac{\rho_0 x}{c_0^2 p_0 T_0}} \]  

where \( p_0 \) is the peak pressure, \( \rho_0 \) is the density of air, \( c_0 \) is the speed of sound in air, \( x \) is the distance, and \( T_0 \) is the temperature.

Figure 1. (a) Acoustic waveform (b) Spectrum obtained at 3 cm from the laser-generated spark using a 1/8” microphone.
\[ T = T_0 \sqrt{1 + \frac{\rho_0 x^2}{c_0^2 \rho_0 T_0}} \]  
where \( p_0 = p(x = 0) \), \( T_0 = T(x = 0) \), \( \rho_0 \) is the density of air, \( c_0 \) is adiabatic sound speed in air, \( \varepsilon = (\rho + 1)/2 < 1.2 \) and \( \gamma \) is the adiabatic constant.

Assuming a peak pressure of 22.163 kPa, and assuming a duration \( t_0 \) of either 12 \( \mu s \) (the positive duration) or 48 \( \mu s \) (the total duration) which are the measured characteristics of the waveform at 0.03m from the spark, the effects of hydrodynamic nonlinearity are predicted to be 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 26 \( \mu s \) at 3cm from the spark. From the data and calculations it may be concluded that, although the spark itself is asymmetric and elongated in the direction of the incoming light beam\(^9\), 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. 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. The peak pressures in 50 shocks have been measured at fourteen source-receiver distances between 20 cm and 150 cm. The results from using a ¼” microphone are shown in Figure 3. The ¼” receiving system has a frequency response only up to 100 KHz. 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 data at each range.

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 0.75 cm, corresponding to grazing angles of 4.29, 3.81, 3.43, 3.12, and 2.86 degrees respectively. The data in Figure 4 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 1,400 Pa (9.4dB level difference) at 20 cm from the laser spark source (see Figure 4).

Nonlinear propagation over rough hard surfaces

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.

Figure 2. Measured reduction in peak pressure with distance in the free-field compared with spherical spreading; 1/8” microphone receiver.

Figure 3. Measured reduction in peak pressure with distance in the free-field compared with spherical spreading; 1/4” microphone receiver, 50 shocks. Error bars represent standard deviations of data at each range.

Figure 4. 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.

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 0.037 cm. This implies time delays of between 1.6 and 1.1 \( \mu s \) at the receiver points. These time differences are less than 2% of the pulse duration, which is between 64.5 and 108.0 \( \mu s \), as shown in Table 1 and may account for the interference effects observed in Figure 4. Without the ground surface, the peak pressures
decreases monotonically with increasing distance, as shown by the free field data in Figures 2 and 3. Surface roughness is found also to cause elongation of the waveforms beyond that expected from nonlinear hydrodynamic effects. Figure 5 compared waveforms received at 30 cm from the laser-generated sparks over smooth glass and the surface formed from 5mm cubic glass grains. As well as reduction in amplitude and elongation, the waveform received over the rough surface shows evidence of a surface wave similar to that observed at lower amplitudes7). 

\[
tortuosity = \left( \frac{\text{Sound Speed in air}}{\text{Sound Speed in material}} \right)^2
\]  

This tortuosity value is very close to the average value 1.067 deduced by fitting data for the acoustic characteristic impedance that have been obtained independently. Similar data and deductions have been obtained with samples of gravel and porous concrete. The results are summarised in Table 1 together with values deduced from fitting impedance tube data and the measured flow resistivities. Not surprisingly, there is evidence that timing the front end of shock becomes a less accurate method for tortuosity deduction as the flow resistivity of the porous material increases. Further work is needed to investigate possible nonlinear and dispersive effects. However, it appears that laser-generated acoustic pulses offer an alternative to the conventional ultrasonic cell method for measurement of tortuosity.

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured Flow resistivity Pasm</th>
<th>Tortuosity from laser-induced acoustic shock data</th>
<th>Tortuosity from fitting impedance tube data</th>
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<tr>
<td>Porous aluminium</td>
<td>204.6</td>
<td>1.07</td>
<td>1.067</td>
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<tr>
<td>8mm gravel</td>
<td>846</td>
<td>1.5</td>
<td>1.46</td>
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<tr>
<td>Porous concrete</td>
<td>3619</td>
<td>1.57</td>
<td>1.8</td>
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</tbody>
</table>

Table 1. Results from tortuosity measurements.

Conclusions

a. The characteristics of laser-generated acoustic pulses are useful for laboratory research into nonlinear acoustic effects.

b. 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.

c. Preliminary measurements of the speed of laser-induced acoustic pulses through thick samples of material suggest the possibility for developing a novel ultrasonic method for determining the tortuosity of rigid-porous materials.

References