Development of Capacitive Sensors for the Study of Detonation

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Abstract

A novel capacitive sensor has been designed and manufactured to allow for spatially and temporally resolved measurements to be made of materials in the time before steady state detonation has developed. The sensors are driven by a high frequency waveform generator and then the effects of the conductive zone within the reaction front alter the shape of the waveform which is then detected using a high bandwidth oscilloscope. Details are given of the analysis routine, along with some examples of the results that are obtainable.

Keyword: capacitive sensing; detonation; conductive zone

1 Introduction

Understanding the reaction zone of detonating explosives requires an understanding of the interaction between shock physics and the chemical reaction process. In the shock physics picture, the reaction zone starts at the initial pressure spike, and ends at the Chapman-Jouguet (CJ) point where the flow is sonic. In the chemistry picture the reaction zone is described by complicated kinetics which may involve multiple intermediate steps and pathways from reactant to products. The ions formed during these intermediate steps give rise to conductivity, therefore the terms 'reaction zone' and 'conductive zone' are sometimes used interchangeably.

Time resolved measurements of the conductive zone of a detonating explosive are an experimental challenge due to the short duration of the reaction (~100ns or less). Further difficulties arise when the measurements are to be made around the transition to steady state detonation, since the reaction zone itself is not spatially invariant. In the steady state situation it is often possible to gain the information required (for example basic parameters such as the detonation velocity) by using larger scale experiments [1].

To date most direct measurements of the conductive zone have been done using resistive sensing – i.e., applying a voltage across it and measuring the current induced, either directly or with an electromagnetic coil. These methods generally use a D.C. source with a high (~1kV) voltage [2], something which could conceivably influence the material or the reaction that is occurring.

The technique described here instead uses an A.C. source, and rather than measuring the resistance through the conductive zone, measures the capacitance between it and a sensor. The voltage of the source can be orders of magnitude smaller (~1V), and the sensors do not need to be embedded within the explosive but can be positioned on the outer surface This increases the confidence that the technique is measuring the actual situation of interest and that the sensors are not influencing the results.

Using time-frequency analysis [3] to magnify small differences between the source signal and the response signal produces a time-resolved conductivity profile. The design of the sensors allows a profile to be measured at several different points in space during one experiment.

The sensing system and analysis technique are described here, as are some demonstrative results using laser-flyer initiated PETN as a subject. It is likely that the system could be further developed to provide additional functionality, or to examine different geometries (for example) than the one presented here.

2 Capacitive Sensing

Passing an alternating voltage across a circuit with capacitance will result in a modification to the shape of the signal without changing the frequency. The degree of signal change depends on the size of the capacitance. A conducting object in the proximity of the circuit will cause capacitive coupling, which will result in a slightly different change to the signal. Exploiting this phenomenon is the principle behind capacitive sensing. The reaction zone in an explosive is one such conducting object, and if the remainder of the experiment is made from non-conducting materials (plastics etc.) then the signal seen at the sensor can only have come from the reaction zone allowing it to be described.

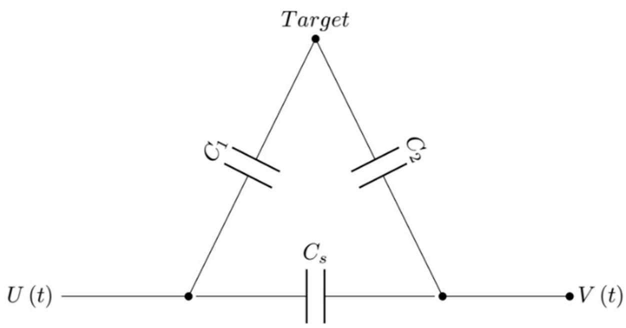

Figure 1. Equivalent circuit for capacitive sensing. New capacitances are introduced by the proximity of a conducting object to the sensor. U(t) is the input signal to the circuit and V(t) is the output. Cs is a known capacitance.

2.1. Transfer Function

The transfer function is the property of an electrical network which describes the mapping of an input signal to an output. Mathematically, if an input signal is described by the function $U(t)$ and the output by $V(t)$ then the transfer function is given by:

$$H(s) = \frac{\mathcal{L}\{V(t)\}}{\mathcal{L}\{U(t)\}}$$

where $\mathcal{L}$ denotes the Laplace transform:

$$\mathcal{L}\{X(t)\} = \int_{-\infty}^{\infty} X(t)e^{-st}dt$$

The conjugate variable s is a complex number $s = \sigma + i\omega$. In non-transient applications, σ can be set to 0 and the Laplace transform reduces to the Fourier transform with ω as the conjugate variable.

In a generalised RLC circuit the transfer function will be a function of the impedances of each component: $H(s; R_i, L_i, C_i)$. The circuit can be designed to maximise the effect of changing any one of these, in this case capacitance.

The magnitude of the transfer function for a fixed frequency input signal is called the frequency response $|H(i\omega)|$. An input signal containing different frequency components will therefore also change shape as well as size in response to a change in the transfer function.

This change underlies the analysis procedure used in this implementation of capacitive sensing – a change in the capacitance of a circuit caused by a conducting region will cause different frequency components to be present in the output signal compared to the input signal.

A good sensing system will be sensitive to small changes in conductivity in the objective sensing zone, while minimising sensitivity to changes to conductivity away from the objective region.

2.2. Active Shielding

One way in which the sensor can be configured to have directional sensitivity is through active shielding. By matching the input signal on the transmitter electrodes with an opposite phase signal on similar shaped electrodes, the potential is zero across any stray capacitance (capacitance outside the circuit) to ground so the transfer function is not affected. Furthermore, by positioning the shield behind the transmitter and receiver, electric field lines are blocked on one side, so the sensor is given directionality. The size of the shield is a trade-off between sensitivity and noise reduction – here the shield has approximately the same dimensions as the electrodes.

3 Sensor System

The sensor system introduced in [4] has three main components: a waveform generator to produce the driving signal, an oscilloscope to measure the output, and the sensors themselves, which are single use circuits. The sensors are designed to maximise the transfer function change while also being cheap to manufacture, since they are inevitably destroyed in the experiments.

3.1. Sensor

The sensors are double layer flexible printed circuits (FPCs). There is a layer of 65µm thick copper etched on each side of 25µm thick polyimide by a photolithographic process. They were produced by P.W. Circuits.

The active part of the sensor consists of a row of pairs of 0.5mm×0.5mm double-layer electrodes.

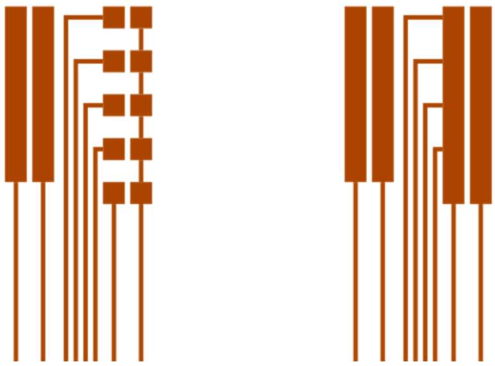

Figure 2. Schematic of the printed copper layers on the head of the sensor.

The top layer of each pair consists of a transmitter and receiver, while the bottom layer consists of two active shielding electrodes. The transmitters are on the same connected electrical network, the shields are all on another electrical network, and each receiver has its own electrical network.

The electrodes in the sensor head are connected to the pads via 0.1mm wide tracks and 0.1mm plated through holes (PTHs). The tracks are approximately 4cm long: any shorter and it would risk more components needing to be replaced after each shot; any further and the tracks' own capacitance would become influential.

3.2. Peripheral Apparatus

Figure 3. View of both layers of the sensor.

The oscilloscope (Tektronix DPO7254) has a bandwidth of 2.5GHz and a sampling rate of 10GS/s. The waveform generator (Tektronix AWG70002A) was set to produce a square wave input signal at 500MHz. The generator's second channel carried the shielding signal with the same shape and frequency but 180° out of phase.

A custom-made junction box was used to route the input signals from the waveform generator into the sensor, and the output signal from the sensor into the oscilloscope. Coaxial cables are used for all the connections in the system to reduce interference. The apparatus can be triggered by a pulse from a detonator, with an appropriate delay set by a delay generator. As this system has been used primarily so far with a laser flier initiator system it has not be difficult to synchronise things (other than the short timescales invovled) as the experiments are very repeatable without significant levels of timing jitter.

4 Analysis

Capacitive sensing has previously been used for small scale experiments to detect conducting objects [5], however, high time resolution (ns) has generally not been important or possible. The raw signal is processed by a digital-to-analogue converter (DAC) chip to produce a real-time capacitive signal, so the time resolution is limited by the conversion time of the chip, which is a few milliseconds. This system omits the chip, and analysis is done on the raw signal post-experiment. In this system the time resolution is limited by either the bandwidth of the recording oscilloscope or the frequency output of the signal generator. If the frequency output is too high for the bandwidth of the oscilloscope to deal with, the high frequency components will not be picked up, but if the frequency output is too low then the system will not react quickly enough to the changing signal.

4.1. Processing

Since the useful data is contained within the spectrum of the raw signal, it is necessary to perform a mathematical transform to extract this information. A pure Fourier transform would lose the time dependence of the signal, so a blended transformation which preserves some degree of frequency and time resolution is needed.

The solution is the continuous wavelet transform (CWT), an operation which produces a function in time and frequency, whose magnitude is the amount of that frequency present in the original signal at that time.

In the continuous wavelet transform, the signal is convolved with a wavelet function – a function that has a characteristic central frequency but is localised in time. There is a trade-off between time resolution and frequency resolution – the narrower the wavelet the better the time resolution. For these experiments the width of the wavelet was set to achieve a 1ns resolution, which proved sufficient to observe the changes in capacitance signal.

One admissible wavelet is the Morlet wavelet, which is a complex exponential confined within a Gaussian envelope:

$$\psi_m = e^{-\frac{t^2}{2}} e^{i\omega_0 t}$$

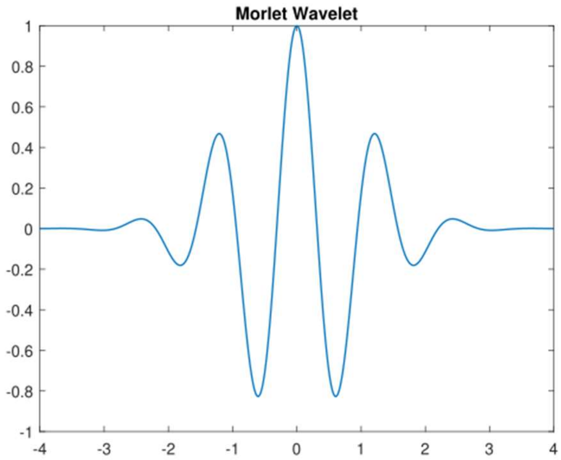

Figure 4. The Morlet wavelet which is convolved with the raw signal in the continuous wavelet transform. Shown is the real part when $\omega_0 = 5$

The CWT is then defined as the convolution in time of the raw signal $g(t)$ with the above Morlet wavelet.

$$W(t, f) = \sqrt{\frac{2\pi|f|}{\omega_0}} \int_{-\infty}^{\infty} g(\tau)\psi_m\left(\frac{2\pi f(\tau - t)}{\omega_0}\right) d\tau$$

CWTs are produced for both the interval of interest $W_a(t, f)$ and a baseline interval of the same length $W_b(t, f)$ immediately before the interval of interest. It now remains to compare the frequency components of these two functions. First the amplitude misfit function is defined as:

$$M(t, f) = |W_a(t, f)| - |W_b(t, f)|$$

The misfit function is then integrated over the frequency domain (in practice this amounts to a sum over the finite number of frequencies of the wavelets used in the convolution).

$$M(t) = \sum_f |W_b(t, f)| M(t, f) \Big/ \sum_f |W_b(t, f)|$$

The misfit function is normalized by the baseline CWT so that the size of capacitive signals from different channels can be directly compared. The rise and fall timing points of the misfit function signal can then be used to derive basic parameters of the detonation wave such as velocity and reaction time.

5 Example Results and Discussion

As part of a larger study into reaction zones, the sensor system was installed along with a laser flyer system to measure the conductive zone of small PETN columns. A schematic of the apparatus is shown in Figure 5.

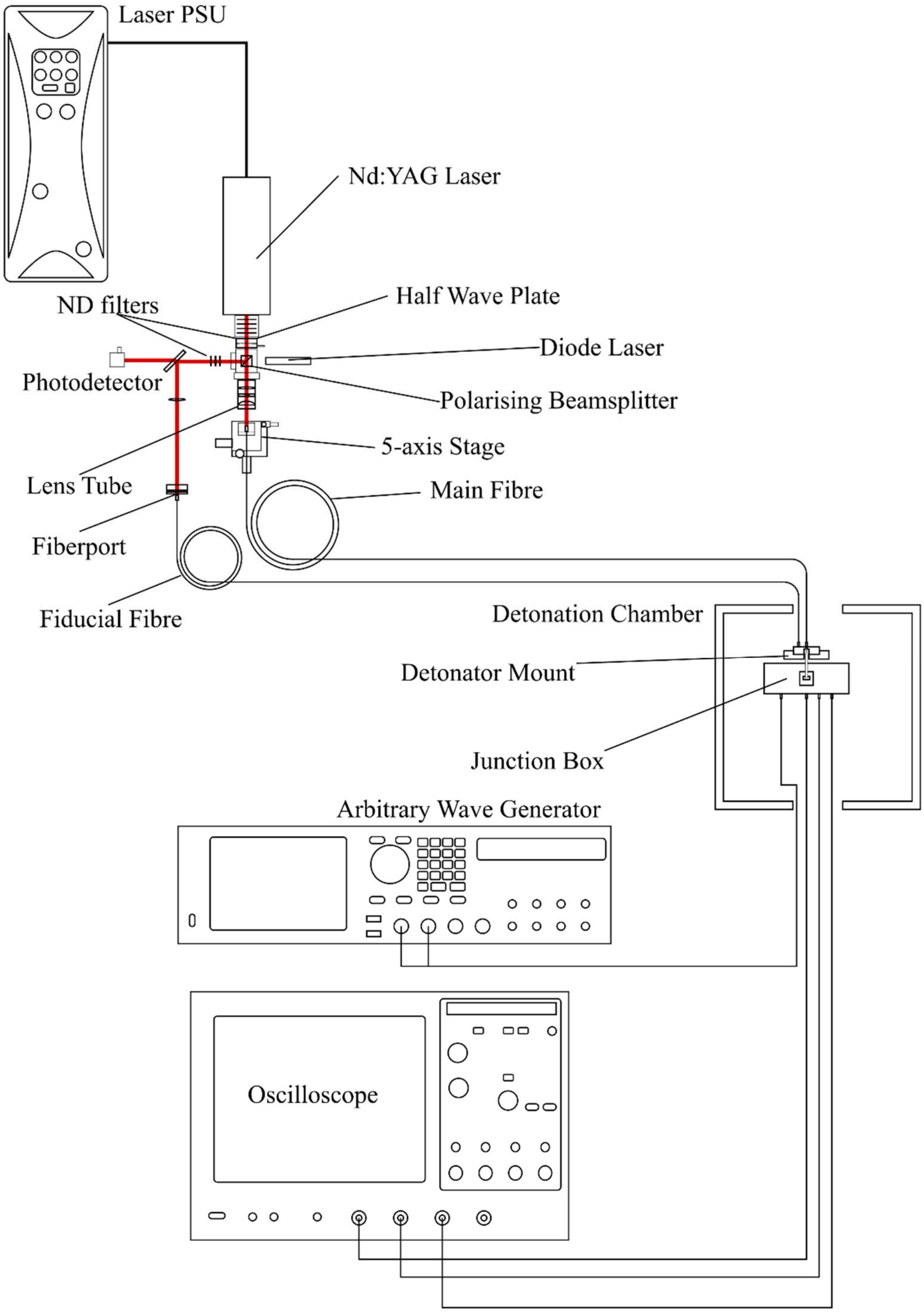

Figure 5. A laser flyer system was used to initiate PETN, and the capacitive sensing system was used to measure the reaction zone.

The sensor was glued into the explosive confinement – a PMMA cylinder – and the PETN was pressed into it. The sensor was placed on the outside edge of a PETN pellet, as shown in

Figure 6, and used to measure the times at which the conductivity rose and fell at several points along the axis.

Experiments were carried out using 1-2μm grain PETN at a range of densities.

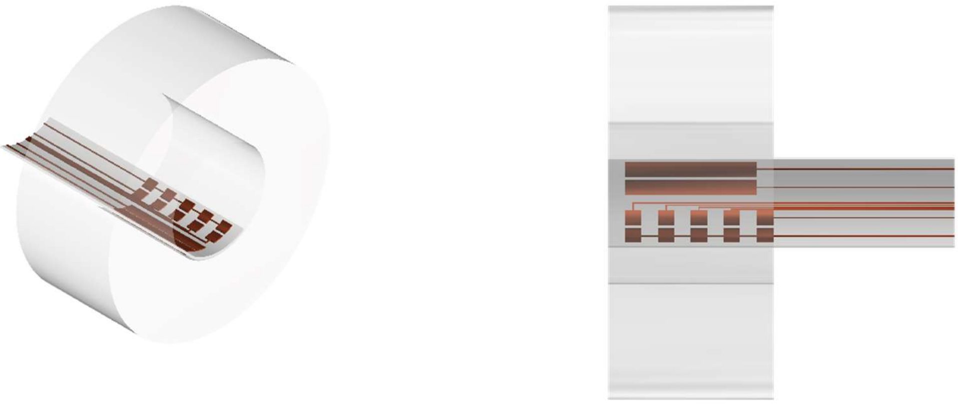

Figure 6. Placement of the sensor head in the PMMA case

5.1. Data

Each channel of the sensor produced a raw signal, which was converted to the misfit signal as described in the previous section. An example of the data produced from one experiment is shown in Figure 7.

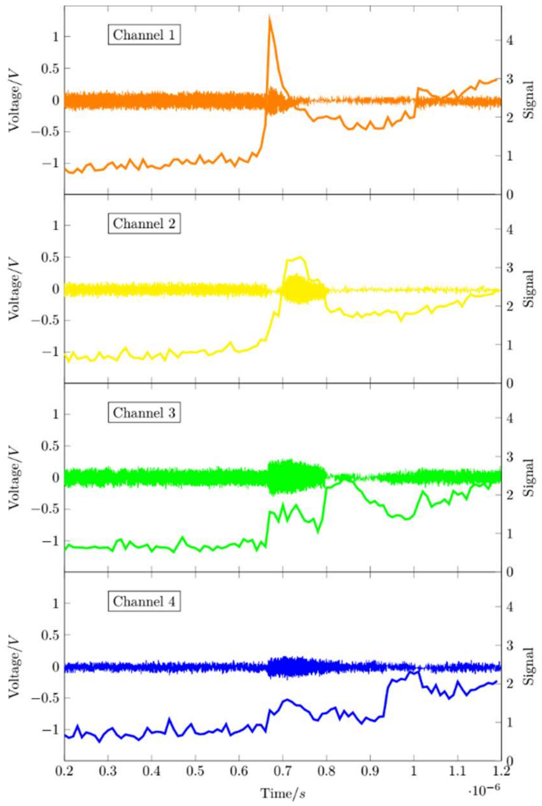

Figure 7. Raw data produced by the capacitive sensing system (thin line) and the transformed signal (thick line). Shown is ultrafine PETN at $1.05 gcm^{-3}$.

Spikes can be seen when the conductive zone passes over the electrodes of each channel. The signal is weaker on some channels than others – the reason for this is most likely imperfect connections within the junction box which filter out certain frequency components.

5.2. Detonation Velocity

Detonation velocities were obtained by time-of-arrival data at each channel on the sensor. The velocities ramped up over the first few mm of the PETN column, until reaching a steady state. These steady state velocities are shown in Figure 8 compared to some literature data [6, 7]

Angular corrections were applied to account for the difference between wave propagation direction and cylinder axis.

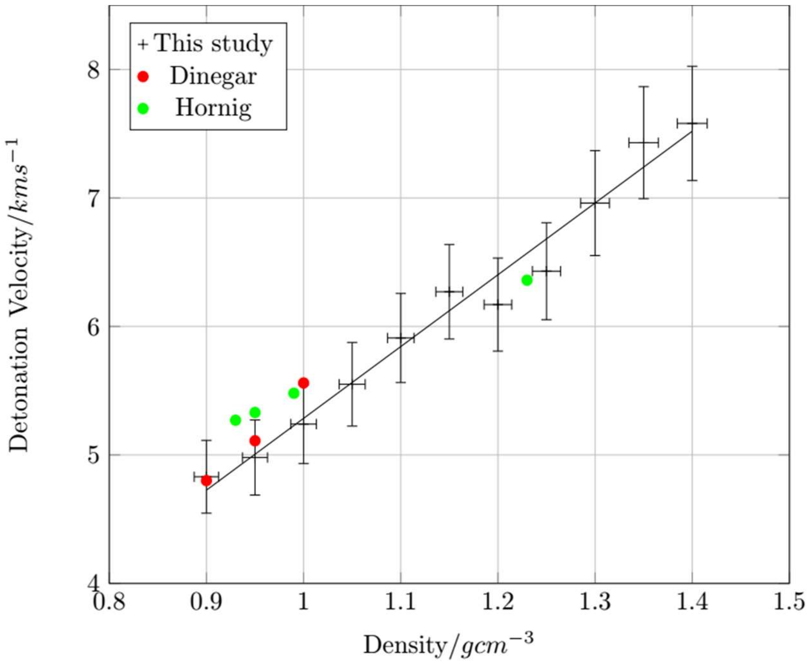

Figure 8. Detonation velocity vs. density as calculated from the capacitive sensor measurements and compared to some literature data [6, 7].

While this method is not the most accurate technique for obtaining a steady state detonation velocity due to small charge length, it does provide credibility to the capacitive sensors as a method for measuring detonation features.

5.3. Reaction Time

From the rise and fall of the capacitive signal it was possible to assign arrival times for the front and rear of the conductive zone at the edge of each channel's receiver electrode on the sensor. From these timing points a characteristic reaction time could then be assigned at each electrode. The steady state reaction times are shown in Figure 9. The reaction time has a density dependence – the steady state is around 14ns at 0.90gcm^{-3} while at 1.40gcm^{-3} it is around 6ns. There is not a very strong consensus within the literature due to different experimental setups, however, these results are between those of Tarver, Breithaupt [8] and Utkin, Mochalova [9].

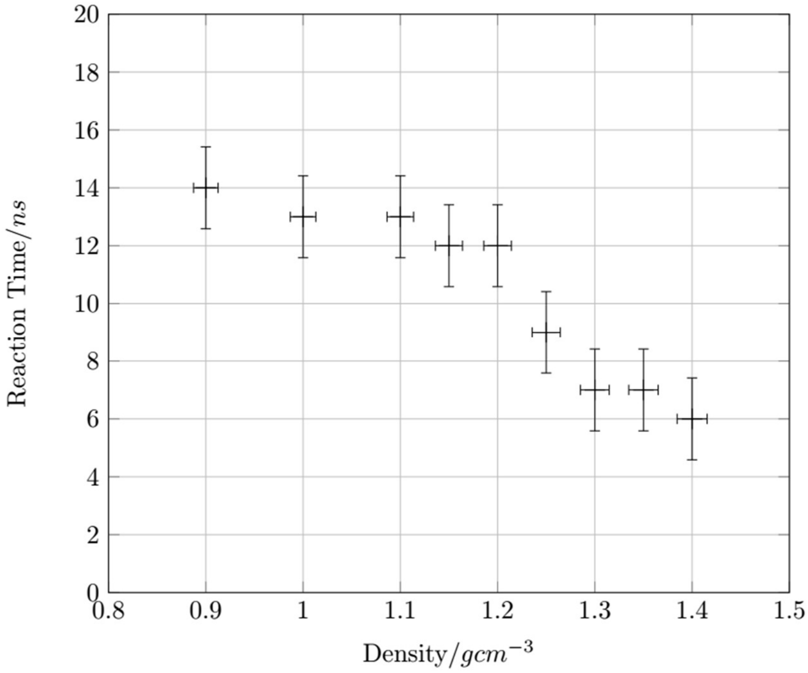

Figure 9. Steady state reaction time vs. density

6 Conclusions

Measurements of the conductive zone in a detonating explosive have been made using a novel experimental diagnostic based on capacitive sensing. A time-frequency analysis methodology was developed to allow post-experiment processing which significantly improves the time resolution over conventional capacitive sensing. The technique was able to accurately reproduce detonation velocity measurements in low-medium density PETN pressings. Measurements were also made of the conductive zone thickness as it develops into steady state following shock initiation by a laser flyer.

The sensors have also been used to measure wave curvature in PETN in experiments not described here.

The concepts demonstrated here are applicable to a wide range of explosive geometries, and further miniaturisation and time resolution should be achievable with different manufacturing technologies and higher bandwidth devices.

Acknowledgement

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