Capacitive Sensing for Measuring Detonations

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Abstract. Novel sensors have been developed to measure the time resolved position and thickness of the conducting zone of detonation waves in columns of explosive. The sensors employ the phenomenon of capacitive coupling to distinguish between the reaction zone, unreacted explosive and reaction products based on the change in conductivity. An electrode is driven with a square-wave alternating voltage, which induces a stronger displacement current in the conducting reaction zone than elsewhere. The size of the coupling effect is then inferred by measuring the relaxation time of the circuit. Unlike some other electromagnetic sensors, these are not embedded within the material, but instead are designed to be positioned on the outer surface. This paper describes the design of the sensors and an initial test. A fibre-coupled laser flyer system has been built to perform initiation experiments.

INTRODUCTION

Diagnostics for detonation measurements exist on a wide spectrum of accuracy, cost and ease to implement. Doppler shift methods such as VISAR and PDV are currently the standard for measuring surface velocity, while for interior measurements, embedded gauges are frequently used. The interferometric methods have a nanosecond response time, but can only be applied to interfaces. Embedded gauges generally either use Faraday's Law to measure particle velocity [1] or piezoresistivity to measure stress [2]. Synchotron X-ray sources are used at the forefront of efforts to understand detonation. Phase contrast imaging can be used to produce micron-resolved images of detonators interacting with explosives [3]. Gustavsen *et al.* [4] performed small angle scattering experiments using synchotron X-rays to infer properties of the reaction zone by the scattering patterns produced by the products. Ershov, Satonkina, and Ivanov [5] identified a significant contrast between the peak conductivity of the reaction zone compared to the unreacted explosive and the detonation products. To measure the reaction zone, they used an embedded axial electrode which induces a voltage in a toroidal coil proportional to the conductivity at a particular time.

Capacitive sensors are proposed as a method to extract information about the reaction zone without requiring the embedding of gauges or electrodes. An alternating current driven through adjacent electrodes couples with the conducting reaction zone - the strength of this coupling is measured during the 'off' phase of the oscillation from the relaxation time of the circuit. This method has been previously used for very high sensitivity applications - Romani *et al.* [6] used a capacitive array to resolve $10\mu m$ polystyrene beads and individual biological cells.

We describe the design of capacitive sensors for measuring chemical reaction zones in detonation waves.

SENSORS

The sensor head is a custom-made double layer flexible printed circuit (P.W. Circuits). A pair of sensors is shown in Fig. 1. To keep the overall sensor as compact as possible the features of the printed circuit were made as small as the manufacturing process would allow. The PTHs (plated through-holes) have $0.356mm$ pads and $0.15mm$ drill holes. The tracks and gaps were the minimum width of $0.101mm$.

The sensor head consists of six measurement zones, one of which spans the whole length of the charge ($4mm$), and the remaining five are $0.5mm$ long with $0.5mm$ spacing placed at regular intervals. A schematic of each side of the head section is shown in Fig. 1. Each measurement zone consists of a channel electrode and three shield electrodes - one adjacent to the channel electrode, and the remaining two on the second layer behind the channel and first shield. The bottom layer of copper extends to the tracks as well as the electrodes themselves to maximise the desired shielding effect.

The shield electrodes are actively driven at the same potential as the channel electrodes, and either in-phase or 180° out-of-phase. The purpose of the in-phase shielding is so that external interference couples to the shield, leaving the channel unencumbered. The out-of-phase shielding works by cancelling with the channel excitation, keeping the target at constant potential. Both the channel and out-of-phase shield see the same capacitance by virtue of symmetry. By performing a differential measurement in this way it is possible to reduce parasitic capacitance; since it is at constant potential it does not feed back to the sensor.

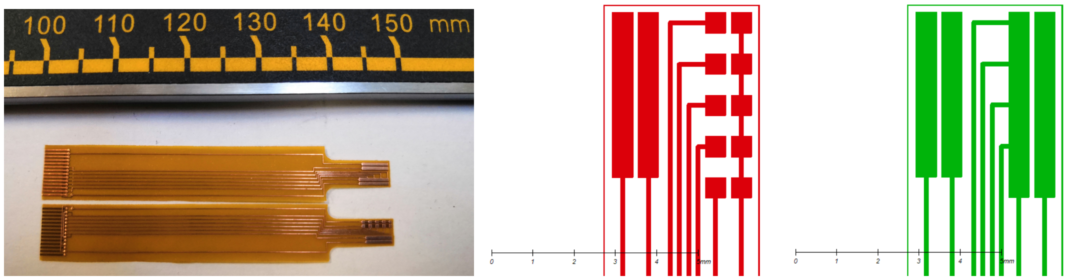

FIGURE 1. A pair of sensors showing both copper layers, and schematics of the head section. One half contains a single, full length measurement zone, while the other half contains five smaller, equally spaced measurement zones. The design emphasises symmetry, both within each measurement zone and between the left and right side.

By measuring the time between the rises and falls of the capacitance measurement on each short measurement zone, it is possible to calculate an approximate velocity history for both the detonation front and the rear of the reaction zone (nominally the Chapman-Jouguet plane). Using these velocities and the timing points it is also possible to calculate the thickness of the reaction zone and its variation with detonation progression.

Figure 2 shows an idealised sensor output for the case where the reaction zone width $\xi < 0.5mm$. The exact value can be calculated as shown in Table I.

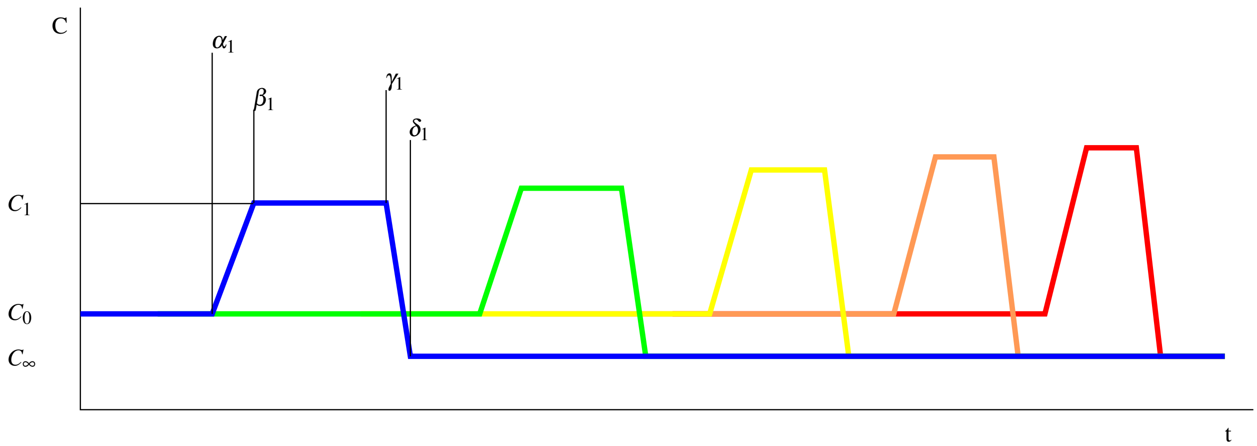

FIGURE 2. Idealised trace from the short measurement zones. The useful capacitances from this plot are C_0: the capacitance of the unreacted material; C_∞: the capacitance of the product; C_i: the capacitance of the i^{th} measurement zone. The useful time intervals are α_i, β_i, γ_i and δ_i; for the i^{th} measurement zone the start and finish of the rise, and the start and finish of the fall respectively. The reaction zone in this trace gets faster, thinner and more conducting with time

The long measurement zone is for tracking the growth of the reaction zone by the size of the capacitive signal. The strength of the measurement is proportional to the conductivity-width product. Since the width can be calculated as described above, the conductivity can also be calculated - this should give some idea as to the progress of the reaction.

In the current configuration, an FDC1004 microprocessor (Texas Instruments) provides the power to the sensor and processes the signal into a 24 bit capacitance value. The capacitive-to-digital conversion performed by this chip places limitations on the temporal resolution that can be achieved. A sigma-delta method is used, which substantially oversamples the signal.

The sensor was tested at low speeds with a small metal probe. A clear signal was observed at each measurement zone tested (Fig. 3). Since the probe was a fixed size, the signal from the long measurement zone remains constant as the probe moves across it.

TABLE I. The method of calculating reaction zone properties based on a trace such as Fig. 2. The continuum approximations are made by interpolating the discrete measurements from the sensor's measurement zones.

Property	$\xi < 0.5mm$	$\xi > 0.5mm$	Continuum approximation
Detonation Velocity	$D_i = \frac{w}{\gamma_i - \alpha_i}$ $D_{i+\frac{1}{2}} = \frac{w}{\alpha_{i+1} - \gamma_i}$	$D_i = \frac{w}{\beta_i - \alpha_i}$ $D_{i+\frac{1}{2}} = \frac{w}{\alpha_{i+1} - \beta_i}$	$D(t)$
Rear Velocity	$V_i = \frac{w}{\delta_i - \beta_i}$ $V_{i+\frac{1}{2}} = \frac{w}{\beta_{i+1} - \delta_i}$	$V_i = \frac{w}{\delta_i - \gamma_i}$ $V_{i+\frac{1}{2}} = \frac{w}{\gamma_{i+1} - \delta_i}$	$V(t)$
Reaction Zone width	$\xi_{i-\frac{1}{4}} = \int_{\beta_i}^{\alpha_i} V(t)\,dt$ $\xi_i = w - \int_{\beta_i}^{\gamma_i} D(t)\,dt$ $\xi_{i+\frac{1}{4}} = \int_{\delta_i}^{\gamma_i} V(t)\,dt$ $\xi_{i+\frac{1}{2}} = w - \int_{\delta_i}^{\alpha_{i+1}} D(t)\,dt$	$\xi_{i-\frac{1}{4}} = w + \int_{\gamma_i}^{\beta_i} V(t)\,dt$ $\xi_i = 2w - \int_{\alpha_{i+1}}^{\gamma_i} D(t)\,dt$ $\xi_{i+\frac{1}{4}} = w + \int_{\delta_i}^{\alpha_{i+1}} V(t)\,dt$ $\xi_{i+\frac{1}{2}} = 2w - \int_{\beta_{i+1}}^{\delta_i} D(t)\,dt$	$\xi(t)$

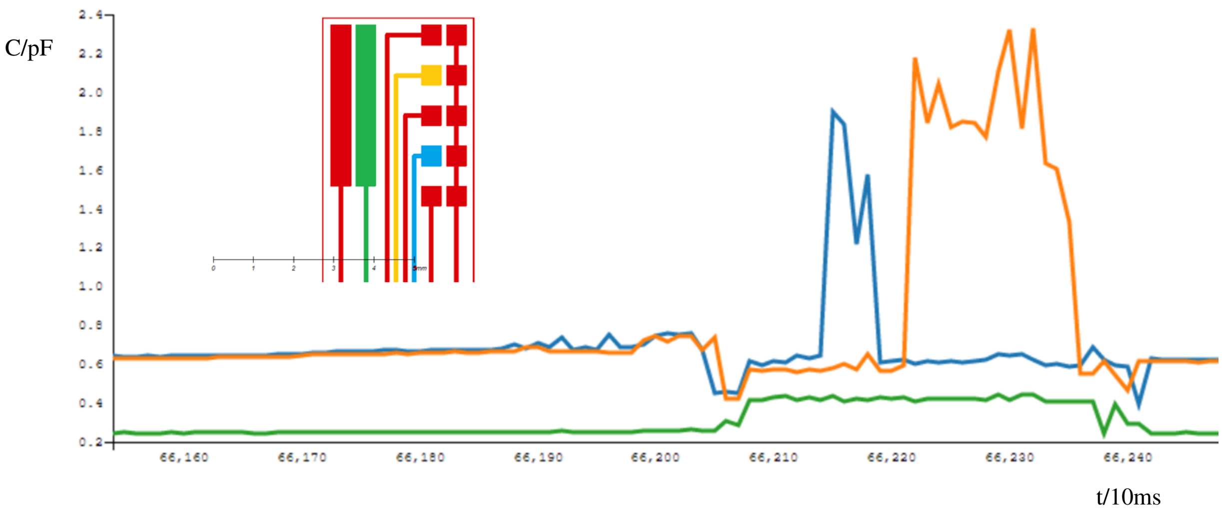

FIGURE 3. Validation of the sensor at low speeds, showing the signals from selected channels

FLYER SYSTEM

Laser flyer systems are commonly used in shock and detonation experiments due to their repeatability and low cost. In this case they have the added benefit of being electrically isolated from the charge and sensors. Our apparatus uses a Quantel CFR400 400*mJ* Nd:YAG laser, which is coupled via optical fibre to the target. The optical path between the laser and the fibre entry is shown in Fig. 4.

Figure 4 also shows a number of laser diagnostics. The CCD camera and InGaAs photodiode measure respectively the spatial and temporal profile of a secondary beam produced by a beamsplitter. By first performing a calibration, an energy meter can also be placed on this secondary beamline to measure the main beam energy on a shot-by-shot basis.

The optical fibre has the effect of reducing the spatial coherence of the beam via modal dispersion [7], resulting in a smoother spatial profile. Irregularities in the laser profile can result in malformed flyers or even total breakup [8].

Figure 5 shows the target assembly, built from a combination of custom-made parts and off-the-shelf Thorlabs components. The kinematic mount allows precise focusing of the laser beam onto the flyer plate with a 20*mm* focal length aspheric lens with an antireflective coating. The flyer plate itself is comprised of aluminium and titanium layers deposited on a glass substrate. The mount plate allows the explosive charge to be probed side-on or end-on by the capacitive sensors or other diagnostics such as streak cameras.

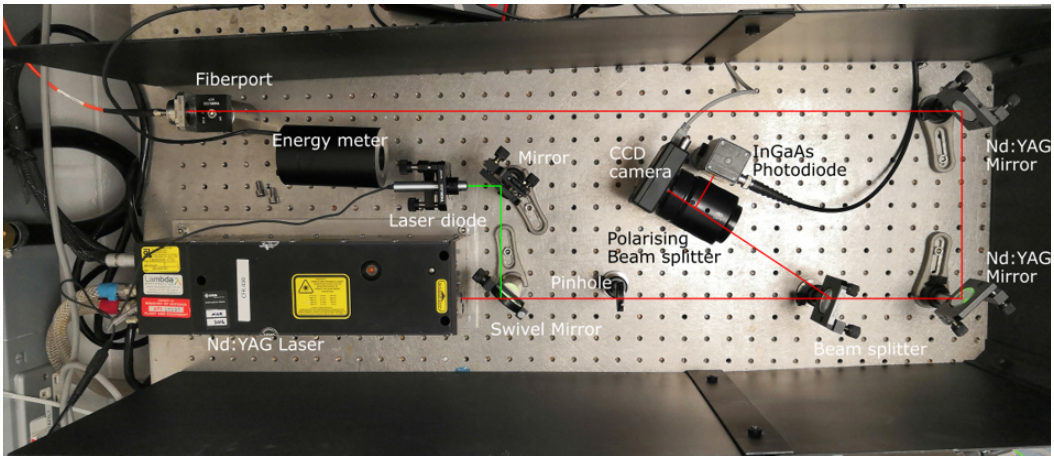

FIGURE 4. The laser flyer apparatus set out on a breadboard. The diode laser is used to perform alignment of the optical components along the main beamline.

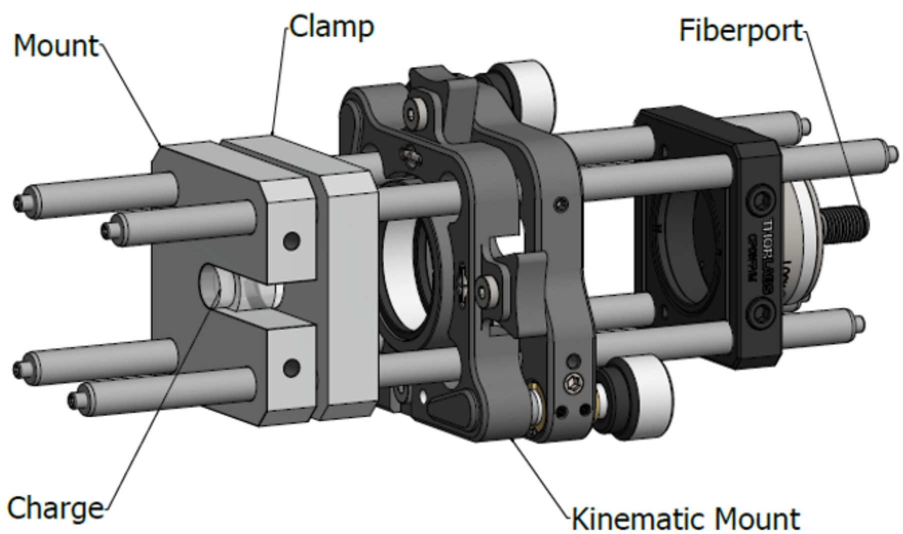

FIGURE 5. The target assembly of the laser flyer system

CONCLUSIONS

New capacitive sensors which measure the conduction zone have been designed for detonation experiments. The sensors have been validated for short length scales and slow conditions, showing promise as a method to measure the conducting reaction zone in detonation experiments. Further work will be done on increasing the time resolution for faster experiments, without the sacrifice of too much accuracy in the capacitance measurement. A system has been for initiating the explosive charge using a laser flyer launched with a high power laser coupled into an optical fibre.

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