ACCURATE LOCATION OF EXPLOSIVE MISFIRES USING A SINGLE CHANNEL DETECTOR

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ABSTRACT
Drill and blast techniques are employed in tunnel construction around the world. A means of confirming that every charge has fired would increase worker safety and productivity. A range of experiments was conducted to determine the spatial accuracy of impulse source location estimates derived from measurements of impulse response signals using a single accelerometer/geophone. Cross correlations of signature-impulse response signals were made with those from positions progressively divergent from the original signature impulse. Trials were conducted using more representative blast-induced impulse signals in situ at a mine. Spatial mapping of the cross correlation of signals measured in a concrete structure showed that positional accuracies of <10cm relative to a signature impulse origin, can be achieved. Early experiments in a mine environment between detonator-induced signature-impulses and to a small production blast showed that spatial resolutions of 40-50cm could be observed. Further tests to establish the viability of this technique at a production scale are planned.

INTRODUCTION
Drill and blast techniques are employed around the world on a daily basis during tunnel construction; in mine heading development. The technique frequently requires scores of individual explosive charges to be fired in a predefined sequence and with a variety of delay times between charges. From time to time the sequence doesn’t fire as planned, or fails to fire completely; with the result that a quantity of explosives and or the detonator used to initiate the explosive, may remain unexploded in the muck pile. The development of a tool to determine the precise location of an underground explosive blast is of interest because of this need to detect and locate misfired explosive rounds.

Prior to this study, the precise behaviour of pre-blast and post-blast impulse cross correlation was unknown. Here we show that employing a single geophone as a sensor, cross correlations of pre-blast, signature-impulse responses with that of the production blast holds promise to aid the identification of each successfully initiated shot and therefore also the absence of any shot that failed to fire. Draeger C, Fink,M, Draeger C, Derode A and Cassereau D [1-5] developed the theory and experimental observations surrounding Time Reversal Mirrors. They demonstrated that a point source impulse injected into an acoustic cavity at a specific location which then passes through a scattering medium, generates a long pulse at remote
receiving points. If the received signals are sampled, time-reversed and then replayed at the respective receiving points, an impulse signal was detectable at the initial excitation point. The experimentation carried out in this study does not attempt to recreate impulses at a point of origin, however it exploits the spatial dependency identified in earlier work on time-reversal mirrors, between an impulse origin and the intervening path to the location of the measuring transducer.

We found that by comparing cross correlations of known signature impulse responses with unknown candidate impulse responses we were able to differentiate the impulse origins. Fig1 shows the behaviour that we intend to exploit in our investigation.

![Figure 1](image)

Figure 1. Comparison of co-located and separated blast-impulse response signals.

Figure 1 illustrates the differences in cross correlation, observed in a mine, between two impulse response signals that share the same origin (left) and, the cross correlation of a pair of signals that have origins separated by 40cm. (right)

EXPERIMENTAL WORK

The research being carried out in this investigation aims to determine whether the time-reversal principles could be applied to blasting and shot firing. A series of scalable impulse correlation experiments was designed to identify the spatial limits of accuracy achievable in the intended context of a sequence of explosive shots.

In anticipation of in situ trials using explosives, it worth noting that these experiments differ greatly from the work conducted by Fink et al in several key respects; namely:

- The acoustic cavity will be damaged or destroyed, in part, or completely during a tunnel production blast.
- Isolating a specific signature impulse in the presence of overlapping or simultaneous impulses from another position(s) may be required
- Inhomogeneity of the acoustic medium

Impulse response correlations in concrete

Given the known inhomogeneity of any rock mass, successful array processing seemed unlikely therefore the use of a single sensor was adopted. We have found that it is possible to successfully differentiate two impulse responses in a concrete slab if their origins are greater than 10cm apart, by comparing cross correlations. The image shows the experimental 1x1m test area, marked out with a 10cm grid. The white circle shows the position of the target location. Impulses were made at each position across the grid. Cross correlation was made between each candidate impulse response and that of the signature impulse from the target
position. Using Matlab, the correlation coefficients were calculated and plotted against the position of the point of origin of each candidate impulse.

The maximum correlation coefficient was consistently observed at the target position.

Figure 2. Concrete slab 1 x1m grid. (10cm Pitch) and Spatial mapping of correlation coefficients with candidate impulse position

**Correlations in the presence of an interferer**

In a tunnelling or mining context it is possible that charges may overlap or essentially fire simultaneously, therefore additional measurements were taken to compare individual impulse signals with the impulse derived from simultaneous pairs of impulses; one at the specified target position and one at an off-target position.

Figure 3. Correlation of two impulse responses with sample, at the same position (left) at 60cm range (centre) and at the target plus an interferer (right).

From Figure 3 that strong correlations were observed even when an impulse response generated at the target origin was overlapped completely with a 2nd off-target impulse.

**Quarry blast experiments**

The technique of comparing pre-blast signature impulses with a full face blast-induced vibration time series signal is complicated by the removal of rock during the final explosion. It was decided to use standard mining detonators to generate impulses for the initial experiments in the quarry. These detonators were fired as individual shots and in pairs. The experiment involved drilling an array of holes that were able to accommodate the detonators in the rock face. A number of individual detonators were fired repeatedly in each hole (where possible) and also two pairs of detonators.

For each of the four target positions (A-D) the cross correlation coefficients were calculated with impulses from other positions.
shows the decay in correlation coefficient as we compare signals from progressively distant positions. We observed that the correlation decays significantly at ranges of around 40cm from the initial point of excitation. When pairs of detonators were fired simultaneously, impulse responses from a target position could be identified in the presence of overlapping off-target impulses.

**Small blast experiment**

The pre-blast signature method was tried with a small production blast at the Camborne test mine. The planned layout and actual timing sequence of the blast is shown in . The time-series signal shows that there were four pairs of charges fired in series, followed by a fifth individual shot.

Comparing the signature impulse from position 3 with the main blast we get the result shown in . It is important to note that despite the removal of significant volumes of rock, correlation could still be observed between the pre-blast signature impulse response and the main blast signal. From we can see that there is a stronger correlation at position 3 than at any of the other positions. It wasn’t possible to carry out a pre-blast signature at the corresponding paired position on that day, but we would expect the 2\textsuperscript{nd} signature impulse to produce a higher correlation at the same timing as number 3.
CONCLUSIONS

From the foregoing experiments detail here, we have shown that the pre-blast signature-hole method holds promise for the detection of misfires in drill and blast operations. We found that impulse responses in inhomogeneous solid bodies are invariant in time, but sensitive to source location. The cross-correlation of successive impulse responses, generated at the same point of origin, is time invariant, but it varied significantly as the impulse origins diverge. As impulse origins diverge, the correlation coefficients decay. The practical classification-range threshold varies depending on the material properties. Differentiation was possible at:

- 5-10cm in concrete, and
- 40-50cm in situ in a rock mass.

Origins of discrete, explosive blast-induced impulses (generated by detonators), separated by distances of 40-50cm, could be identified using this method. Initial results involving rock removal in a production blast indicate that a pre-blast signature impulse can produce an identifiable correlation with a production blast shot at the same location. This correlation is distinct from correlations from off-target impulse responses. This could allow the technique to be applicable in the context of production drill and blast.

FUTURE WORK

Investigation will continue to improve the correlation classification by:

- Employing additional sensors to add detector spatial diversity, and
- Signal preconditioning to improve the signal to noise prior to making correlation.

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REFERENCES
