With Compliments

The Effect of Timing Precision on Control of Blasting Effects

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1. Abstract

Timing scatter limits what blasting results can be achieved and has a major effect on reproducibility. Dynamic blast phenomena occur in different timing windows, and the variability of the timing within any window needs to be within 30% of the desired interval. The quantum leap in accuracy offered by digital timing for detonators opens windows that were not accessible before, but the precision of electronic detonators varies considerably, and this can affect their performance in the field. There is a tendency to assume that "digital timing" means "no scatter", and little awareness that long absolute digital delays can result in significant scatter for shot intervals. In general, absolute scatter increases with delay time; for very long blasts there can be significant loss of control for the end holes. With restricted "time out" not only the maximum delay but also the inter-shot delays are limited.

2. Introduction

Until 1993, the use of digital delay detonators was restricted to trial quantities of systems in various stages of development, and there was widespread doubt that, other than in very specialised

applications, these would add value to the blasting process. The ExEx 1000 programmable detonator system and its associated Computer Aided Blasting concept was launched in South Africa during 1993, and for the first time, major blasting operations were undertaken using detonators connected to a

computer in which the layout of the holes and the required timing was stored. Although there were some problems, and the system underwent a number of withdrawals while technicalities were sorted out, it was used very successfully in large opencast coal mines, massive diamond mines and quarries.

The system was upgraded from a 5/6 wire system to the 2 wire Smartdet™ system during 1998, by which time not only were there two more manufacturers of digital detonators in South Africa, but other systems had been introduced globally, and a broad spectrum of publications had been presented, in each case detailing outstanding improvements in blast performance. These improvements are typically in the following categories

- more uniform, and more predictable range of rock fragmentation sizes
- significantly reduced vibration levels
- ability to control the ground frequency of blasting vibrations
- much enhanced ability to reduce wall damage
- improved advance in tunneling and reduced toes in opencast mining
- improved control over movement of ground
- ability to open drilling patterns and use less explosives while achieving good blasting results
- ability to record detail of blasting layouts and consumption of detonators and explosives
- ability to track production rates

Despite these incontestable achievements, there is considerable angst over how to use these systems to the best advantage, and even a sense of outrage on the part of some, that we do not have a recipe book which enables us to prescribe, to the millisecond, the precise blasting outcome which might be required. Having been involved in the planning, execution and evaluation of many digital blasts, and being convinced as to the potential merit, what follows is a necessary background for understanding their potential, their limitations, and how best to apply them.

3. Blast Timing Capability

Pyrotechnic Delays

It is well known that pyrotechnic timing systems are intrinsically limited in precision, and that no manufacturer can guarantee the timing precision achieved in the field. This is both because of restrictions in manufacturing capability, and the effect of physical factors introduced in blasting, such as length of time since manufacture, temperature, and preconditioning by stress pulses from surrounding holes.

Statistically, each manufactured batch tends to fall within a normal distribution, the deviation of which varies between detonator batches. The mean firing time of these batches also varies, so in-plant standards must specify both the range of allowed means, and the range of variation about the mean. Testing of elements and final product results in destruction of the product tested, so only a small percentage of production can be tested, and the results of the test must be taken as characteristic of the remaining product. If the product fails, then the whole batch must be discarded. Therefore, the tighter the specification, the greater is the percentage of discard and the greater the cost.

Typically, the variation is taken to lie on a normal curve, and the index of variation is the standard deviation σ expressed as a percentage of the mean delay Tm. This is called the CoV, Coefficient of

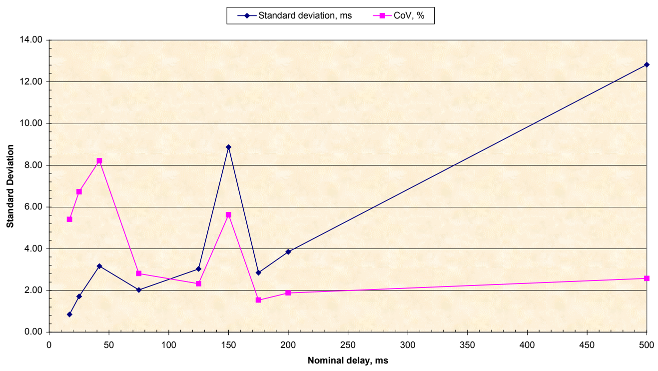
Variance: $CoV = \sigma / Tm \times 100\%$ Eq (1)

In order to keep delay detonator tube length within reasonable bounds, various powders have to be used for different delay ranges, and up to three different delay elements might be used to achieve a particular delay period. Inaccuracies arise at the interfaces between elements, as well as the general drift within any given powder. As a result, the CoV varies between detonators, tending to be worst for very short and very long delays. The inaccuracy of the latter is due to the difficulty of achieving consistency in slow burning rates.

With short delays, a large percentage error still amounts to a small absolute error, so there is not normally much difficulty with these. The main system error arises from long in-hole detonators. Figure 1 illustrates the way in which precision can vary across a range of detonators: the figures are from an actual field test: another test could produce different values, but will have a similar trend.

Figure 1: Variation of precision with delay period for pyrotechnic delays: typical outcome of test, showing deteriorating scatter but improving CoV with length of delay period.

An implication of the foregoing is that as a shot progresses, the precision of timing reduces,

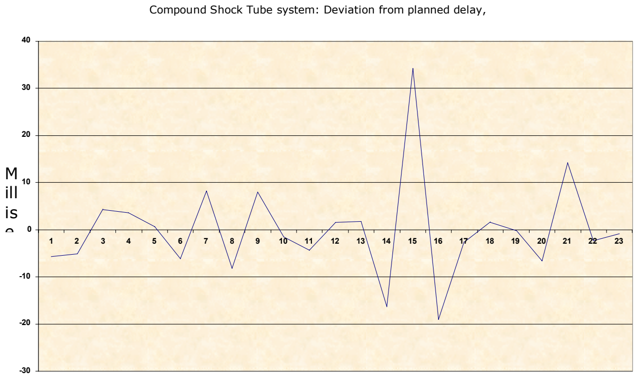


as scatter increases with time. This is seldom the case where large numbers of holes are used, since there is a need to have simple, easy to use systems in quarries and large opencast mines and it is now normal to use constant in-hole delays with the interval provided by a shorter delay outside of the hole. The surface delays have less variation, as they are typically less than 100ms and therefore susceptible to no more than +10ms. However, the variation of the in-hole detonator is transferred to the whole system, and since it is a long delay, a real precision penalty is incurred: the scatter on the longest delay used becomes the minimum scatter on the system.

The system scatter can be taken as:

$$\sigma_T = \sqrt{(2\sigma_1^2 + \sigma_2^2)} \quad \text{Eq (2)}$$

Where
σ_T = Standard deviation of detonator system



σ_1 = Standard deviation of in-hole detonators
σ_2 = Standard deviation of surface detonators

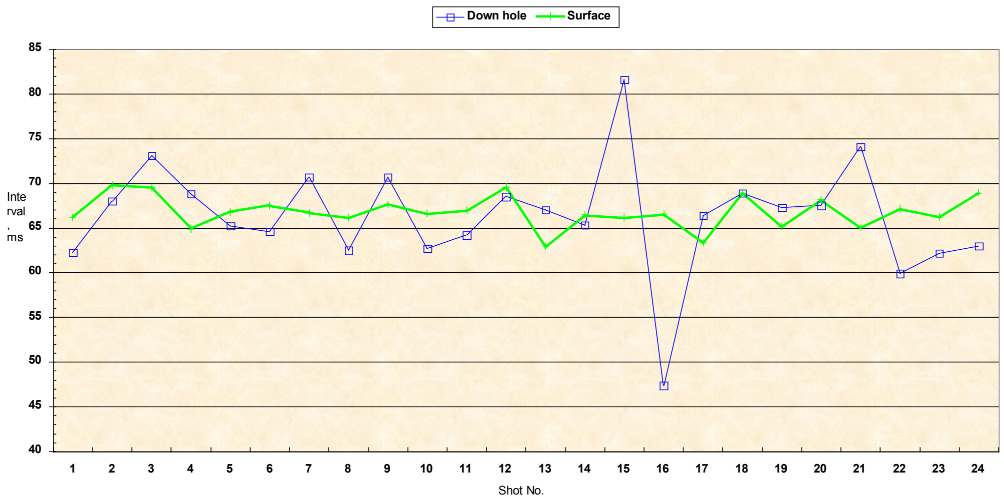
In order to illustrate the reality of what is produced, Figures 2 and 3 show the timing result for an actual blast using very accurate pyrotechnic delay detonators with the following characteristics:

Nominal delay ms	**Mean, ms**	**σ, ms**	**CoV, %**
450	448.2	4.1	0.92
65	66.8	1.8	2.64
System: 65ms	66.3	6.1	9.04

Figure 2 shows the achieved firing times on surface, and with the detonation of charges in the holes.
Figure 2 achieved surface and in-hole timing for accurate Shock Tube system: inter-hole delays vary between 47ms and 82ms.
Although this performance is excellent, the maximum delay was 82ms and the minimum 47ms.

Figure 3 translates these results into the important information: how far each shot is from the required time. The key question is, "How much does it matter that achieved timing is different to designed timing?" The answer is, "It depends on what you are trying to achieve, and how far the achieved timing is from what is required."

Inter shot delays - Pyrotechnic Systems



4. Windows for Blasting

Blasting is a complex process which begins with very fast and short-lived strain waves, progresses through crack growth, expansion of the rock mass, and terminates with deposition of the fragments in a muckpile. Different aspects of the blasting result are greatly influenced by whether or not the relevant mechanisms are active when holes in the same row, and holes in the rows around it, fire. These periods of activity can be termed "Windows", and some (by no means all-embracing) guidelines are tabled below. Note the difference between "Interval" and "Window": the interval is the precise delay required within the relevant window. Thus we may know that a mechanism will be influenced within a window of 20 to 80ms, and thus select an interval of 65ms.

Mechanism	Intra-row Window Th ms/m	Inter-row Window Tr. ms/m	Comment
Splitting	0.0 – 1	+30	
Fragmentation	0 – 6	+10,+100, 1000	Various regimes
Movement	0 – 10,	6 – 100, +1000	Various regimes
Vibration	0-5	5-20	Continuous effect

The issue is clarified by taking an example. Suppose that we know that in order to achieve quality splitting, these holes need to fire within 1ms of each other, and that if the timing between these holes is more than 5ms, then no useful effect will result. In addition, suppose that we know that the best result will be obtained if these holes are fired last, with at least 100ms between them and the previous row of holes, which, for reasons of vibration control, need to fire at least 8ms apart. Split holes are divided into groups to be themselves delayed by 8ms in the interest of reduced vibration. A layout illustrating this and showing what might be in the mind of the designer is given in Figure 4.

If the timing is to be done using in-hole pyrotechnic delay detonators, with a system standard deviation of 6ms, then two of the above criteria cannot be met: with a total range of + 18ms, the production holes can fire up to two holes out of sequence, let alone being able to provide any guaranteed interval of time between the holes. The 8ms window is thus missed.

The split itself is likewise compromised, since there can be no expectation of getting within the 1-5ms window required.

The window of 100ms between the production and the split holes can probably be met, although there is a possibility of an early shot resulting in say 80ms instead of 100ms between production and split holes.

Confidence Ratio

From this one example the limitations of pyrotechnic delays are very evident: the next question is, what windows can be addressed by a system whose characteristics are known? Figure 5 gives the answer to this question. Since extent of control is defined by the system standard deviation, and the range can be taken as + 3 times the standard deviation, the time window delay between holes must be related to this. The measure required is the timing Scatter Ratio, defined thus:

$Rs = (6\sigma T / Tw) \times 100\%$ Eq (3) where

Rs = Scatter Ratio: if Rs < 100% then the variation of the timing system is less than the breadth of the timing window.

σT = System standard deviation: assume that $6\sigma T$ will represent the full scatter for firing times. If the scatter is more than the window, there is no possibility of control.

Tw = Interval required to exploit window of opportunity for blasting effect, ms. If Tw is the intershot delay, then for sequential firing, Rs < 100%

This function is shown in Figure 5, both for the high precision delays shown in Figure 2, and for the lower precision system of Figure 1.

We now need a criterion for deciding whether a particular Scatter Ratio is acceptable in any application. This is a combination of science and personal judgement, looking to what is helpful versus what is ideal. The ideal situation would be that the timing interval achieved meets the timing interval specified within a range of +1%. However, the lack of control over other parameters, and the duration of the mechanisms addressed by the window, can tolerate a much wider spread than this in most situations. As a worst case starting point for gaining control over a blasting phenomenon, it is suggested that the maximum tolerable value for Rs should be 30%, i.e. that the total range of the system delivers an interval of + 15% of what is required: this means that the system standard deviation, σT, should be not more than 5% of the interval. This is illustrated in Figure 6, indicating the maximum variation for a 100ms desired interval. Note that although the interval is 100ms, the detonator delay is from initiation of the blast sequence, which could be very much longer. The error might be small relative to this long delay, but great relative to the inter-shot interval.

Precision of Digital Detonators

While the demands on the system may seem to be achievable with digital electronic delay detonators, it should be remembered that these systems also have limitations. There are two main approaches to achieving digital timing:

- the use of a quartz crystal, as in AEL's Electrodet™ system,
- the use of a self-calibrating oscillator, as is employed in AEL's Smartdet™ system.

Quartz crystals should yield the most precise timing: for Electrodets™, a maximum error of 1ms is achieved for all delays. This precision may seem rather low for electronic timing, and is elevated as a result of every detonator having a 32 000ms in-hole delay. This configuration, with pre-set inter-hole delays is particularly effective for applications of large numbers of holes where the simplest possible hook up procedures are required. The 1ms error is negligible in the context of most blasting windows.

For oscillator systems, the error can be significantly greater. Our initial system, the ExEx1000, had a CoV of 0.1%, which means a standard deviation of 1ms per 1000ms in-hole delay. A 100ms delay will have a σ of 0.1ms, while in a blast of 10 seconds duration, the last detonator to fire would have a σ of 10ms, giving a total error range of + 30ms. If the interval required between shots was 25ms, this would be easily achieved in the early shots, but from about half way through the blast, no control would be achieved, and towards the end, out of sequence firing would be possible. This is illustrated in Figure 7, which shows that once the time from blast initiation exceeds 13 seconds, electronic timing for systems of this precision become worse than constant in-hole delay shock tube systems. This is of particular interest in underground applications.

Fortunately, most surface blasting uses shots of less than 3 seconds duration. In the Smartdet™ system which succeeded the ExEx1000 system, the CoV has been reduced to 0.01%, ie yielding a range of + 0.03ms per 1000ms of duration. This eliminates control problems in the huge majority of situations. Clearly, the specifications of digital timing systems need to be understood and applied to each application, and the assumption may not be valid that electronic timing automatically means acceptable performance in the field. Certainly, where control is needed over vibration

5. Timeout for Digital Detonators

For various reasons, there is a limit on the time over which a digital detonator can function. This "timeout' in turn limits the size of blast that can be undertaken. For example, if the timeout is 3 seconds, then a maximum of 100 holes can be fired with a delay of 30ms, and only 10 holes can be fired if the delay per hole is 300ms. This reduces the range of delays which can be selected, since if there were say 75 holes to fire, the longest delay that could be given between every hole would be (3000/75) = 40 ms. With Smartdets™ the timeout is 20 seconds, which provides great flexibility for underground blasting.

6. Conclusion

Understanding the consequences of various levels of timing precision leads to strategies for blast timing which address the windows of blasting activity, and it quickly becomes apparent that not much is possible with pyrotechnic delays. This partly explains the huge variation in, for example, vibration amplitudes and frequencies when blasting at a given scaled distance.

Blast timing is the last of technologies to progress into the digital age. The use of pyrotechnic devices is likely to persist owing to their reduced cost and simplicity of use, but as understanding of the price of unpredictable timing begins to impact on explosives users, they will inevitably accept the discipline of using electronic timing in order to harness the resulting benefits.

The implications of this scenario are far reaching:

With pyrotechnic delays it is only possible to gain consistent control over the very slowest mechanisms of blasting, such as movement. Even then the extent of control is limited. This explains much of the variation we see in blasting measurements.

Digital delay detonators are the only hope of achieving control over blasting, but even with these, we need to be aware of the limitations with different systems.

All of the rules used for guiding blast design have been built up on tests conducted with pyrotechnic delays. These rules have therefore arisen with limited ability to penetrate the windows of control, and are valid only for very coarse blasting practice. There is enormous potential to discover the real potential of blasting, both for efficiency and safety.

7. Acknowledgement

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