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*Materiały Wysokoenergetyczne / High Energy Materials, **2021**, 13, 143 − 156; DOI 10.22211/matwys/0211*
ISSN 2083-0165

Research paper / Praca doświadczalna

Determining the timing accuracy of electronic detonators using different methods
Oznaczanie dokładności opóźnienia zapalników elektronicznych przy użyciu różnych metod

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Abstract: *The timing accuracy of detonators used in the mining industry has a significant influence on the safety and effectiveness of blasting operations. However, the accuracy of the time delays in electric and non-electric detonators is unpredictable and may differ from the intended timing due to the pyrotechnic delay element. The latest generation of electronic detonators provide a very high precision of firing compared to pyrotechnic ones. Different methods may be used to determine a detonator's delay accuracy. Selected methods were evaluated in order to identify the most appropriate one for electronic blasting cap testing. The research involved an electroacoustic sensor, an amplifier with an open-circuit probe, a high-speed camera and a data recorder.*
Streszczenie: *Dokładności opóźnień zapalników stosowanych w przemyśle górniczym mają istotny wpływ na bezpieczeństwo i efektywność robót strzałowych. Tymczasem, dokładność opóźnień zapalników elektrycznych i nieelektrycznych jest nieprzewidywalna i może różnić się od zamierzonego czasu z uwagi na pirotechniczny element opóźniający. Zapalniki elektroniczne najnowszej generacji pozwalają na bardzo dużą precyzję odpalania w odniesieniu do zapalników pirotechnicznych. Do oznaczania dokładności opóźnień zapalników stosuje się różnego rodzaju metody. W ramach artykułu przeprowadzono ocenę niektórych metod oznaczania dokładności opóźnień zapalników, co miało na celu wskazanie metody najbardziej odpowiedniej do badań zapalników elektronicznych. Badania obejmowały czujnik elektroakustyczny, wzmacniacz pomiarowy z sondą rozwarciową, szybką kamerę i rejestrator danych.*

Keywords: *blasting, detonators, delay precision, quality control*
Słowa kluczowe: *technika strzałowa, zapalniki, precyzja opóźnienia, kontrola jakości*

1. Introduction

In order to achieve the highest blasting efficiency, an explosive should be initiated in such a way as to obtain a stable detonation within the shortest possible length of the blasthole. Moreover, it should be detonated with the greatest possible accuracy in time as defined in the firing pattern. The idea behind the use of delay detonators is to detonate the explosive in the subsequent blasthole once ground movement has started in the previous hole (resulting from the fragmentation and heave produced by the explosive). It means that such firing times and sequences for individual holes should be designed to ensure that the explosive will detonate only once the displacement of the rocks has already occurred as a result of the detonation of the previous charge, i.e. once the unextracted rock mass has been fractured. This issue is particularly important in underground mines, where blasting is carried out at a single exposed surface. In such cases, the explosives in the cut holes must be precisely fired with the effect of explosion being directed towards the empty (unloaded) holes, which provides an additional surface of exposure [1].

The delay times between the individual holes or groups of holes are selected depending on the planned burden and the spacing between the holes. The use of delays enables the effect of blasting in the form of proper fragmentation to be controlled, as well as minimizing the paraseismic vibrations generated by detonation, especially in the case of open-cast mines.

As pointed out by Onderka [2], using too short delays between holes may have an effect similar to simultaneous firing. This may result in a limited creation of additional exposure surfaces and an increase in vibration intensity, however, it may also improve fragmentation. In turn, using too long delays has a positive effect on the formation of surface exposure, but does not guarantee adequate fragmentation and may lead to amplification of vibrations. This has a negative impact on the surroundings in the case of open-cast [3], but may be an effective method of rockburst prevention in underground mines [4]. Therefore, the key issue is the proper selection of delay intervals between the blastholes [5].

Basically, the accuracy of commonly used mining electric and non-electric detonators is about ±1%. However, due to the fact that the delay element in these detonators is a pyrotechnic, it can be as high as 5% [6-8]. Consequently, achieving high firing accuracy with this type of detonator technology is very difficult. Due to this lack of accuracy, electronic detonators were developed – they have a chip into which a delay time can be programmed. The delay times in such detonators may be defined in 1 ms intervals with an accuracy of ±0.1 ms (depending on the specific system), which is impossible to achieve when using traditional pyrotechnic detonators [9]. An additional bonus of these detonators is the improved safety and efficiency of blasting operations [10].

Despite their high cost, electronic detonators are a preferred alternative to pyrotechnic detonators in specialized mining, tunneling and civil engineering blasting [11, 12]. Programmable detonators are therefore widely used as a tool for reducing vibrations induced by detonation of explosives in mining [13-15] or tunneling [16, 17], but also as a tool for improving rock fragmentation [18, 19]. As noted by Digay [20], they are also an efficient tool for selective (resue) mining.

Given that the precise initiation time of an explosive is a key influence in the final result of blasting, it is justified to conduct periodic measurements verifying the delay times declared by the manufacturers. In such measurements, both standard test procedures [21] as well as alternative methods [22-24] may be applied. However, the test procedure to assess the timing accuracy of electronic initiation systems has not been harmonized so far and exists only in the form of a normative document [25, 26]. Since electronic detonators are far more accurate than other types used in mining, this study presents an assessment of four methods for determining the timing accuracy of electronic detonators, to identify the most appropriate method. It was assumed that the accuracy of the determined delay depends only on the applied method, therefore the delay of each detonator was determined by all the methods simultaneously. The research involved an electroacoustic sensor, an amplifier with an open-circuit probe, a high-speed camera and a data recorder. The evaluation of measurement methods was based on both a statistical analysis of the results and an assessment of the degree of difficulty of the test procedure. Additionally, estimated costs of testing using the individual methods, are presented.

2. Legislative background

According to the European standard [21], the delay accuracy of detonators must be determined with a timer or an oscilloscope. However, the specific parameters or types of the devices to be used are not defined.

Nevertheless, the requirement concerning the measuring accuracy must be fulfilled, which cannot be greater than 0.1 ms for the entire measuring system. According to the above standard, the start pulse for electric detonators may be given by the firing unit providing an electric impulse once the firing current is applied, whereas for non-electric detonators this can be from optical or pressure sensors. The stop signal on the other hand may be given by an optical or pressure sensor, which indicates the initiation of the base charge of the detonator or external connector. However, the standard does not specify the required type of apparatus, which enables the use of many types of sensor, while maintaining the measuring accuracy of 0.1 ms.

The above standard refers only to the testing of pyrotechnic detonators, i.e. electric and non-electric. As mentioned above, the requirements for electronic initiation systems have not been published as a harmonized standard, so far, and exist only as a normative document, which should be treated as a draft standard [25]. Para 4.5.6.3 of this document describes the method for determining the delay accuracy of electronic detonators, whereby testing can involve both the electronic part (without pyrotechnic) and the complete detonator. Thus, it is permissible to use dummy detonators when determining the delay accuracy of the electronic part of the detonator.

The test requires the accuracy of 20 detonators or 20 dummy detonators having programmed delay times of 10%, 25%, 50%, 75% and 100% of the full time scale specified by the manufacturer, to be measured. If the tests are conducted on dummy detonators, then 20 complete detonators shall be tested in addition, at approximately 25% and 75% of the full time scale. For all types of programmable electronic detonators, 20 detonators from each of two consecutive delay numbers, at approximately 25% and 75% of the time scale specified by the manufacturer, must also be tested in order to verify that the risk of overlap is insignificant. All these tests are conducted at three temperatures – ambient, minimum and maximum, as recommended by manufacturer.

A dedicated firing and/or programming and/or testing unit as specified by the manufacturer of a given initiation system should be used. As with the standard defining the test procedure for pyrotechnic detonators, the draft standard for the electronic systems does not specify the type of measuring apparatus. It can either be a timer or an oscilloscope, equipped with the means of measuring the delay time between the start and stop pulses, but with an accuracy of 0.01 ms, which is 10 times greater than that required for pyrotechnic detonators.

The start pulse can be provided either by a signal given by the firing unit, or by a detonator with a zero delay (as specified by the manufacturer). On the other hand, the stop pulse can be triggered by an optical or pressure sensor providing an electric pulse when the base charge is initiated (for complete detonators), or by a sensor adapted to the device used to replace the fusehead, providing an electric pulse when the device simulates the initiation (for dummy detonators).

Before testing, detonators or dummy detonators must be conditioned for at least 2 h at the temperature specified by the manufacturer. Before conditioning, the delay times must be programmed. After testing, the mean value (t_m) and the standard deviation (s) are calculated for each tested interval, and the accuracy of the system at ambient temperature is determined. In order to determine temperature dependency, the results obtained at minimum, ambient and maximum temperature should be compared. The results are considered correct if $t_m \pm 3$ s for each interval is within the range specified by the manufacturer. Furthermore, it must be verified whether the risk of time overlap between two consecutive delay intervals is significant. If so, then this information should be provided to the user.

3. Material and methods

As the draft standard covers the testing of both complete detonators as well as the electronic part, the authors carried out a series of tests of detonators complete with base charge, using selected measurement methods. The purpose of the tests was to identify the most appropriate method for determining the delay accuracy of electronic detonators and to define the limitations of these methods. These involved the following measuring devices:

– electroacoustic sensor,

- measuring amplifier with an open-circuit probe,
- high-speed camera,
- data recorder for continuous detonation velocity measurement.

It should be noted that these methods are characterized by different sampling rates. Not all of them fulfil the requirements of the draft standard with regard to the sampling rate [25]. Nevertheless, they were subjected to a detailed analysis based on calculations of the mean value and the standard deviation, and on an evaluation of the degree of test procedure difficulty.

Electronic detonators produced by a domestic manufacturer of blasting agents, with a base charge of 0.75 g PETN, were tested. The delay interval for the analyzed system is 1 ms. According to the technical data sheet, the delay accuracy (scattering) depends on the programmed delay time and amounts to:

- 0.1 ms in the range of 0 to 99 ms,
- 0.10% in the range of 100 to 1499 ms,
- 0.05% in the range of 1500 to 15000 ms.

One detonation time of 3750 ms was selected for the testing, which corresponds to 25% of the analyzed system time range. The tests were carried out on 20 detonators, as per the standard requirements, using all the methods simultaneously (on the same detonators). They were carried out at the Central Mining Institute's test site in Mikołów, Poland. Due to the limited number of detonators, the tests were carried out only at ambient temperature, which on the day varied within 1-2 °C. Detonators were programmed prior to testing and then conditioned for 2 h at ambient temperature. It should be noted that, according to the technical data sheet, the analyzed detonators can be used at temperatures ranging from –20 to +60 °C. The procedures for determining the detonator delay accuracy using the individual methods are presented later in this section.

3.1. Electroacoustic sensor

This measuring system uses an electroacoustic sensor, which converts sound waves into electric signals. The system records the time between two sound signals, i.e. time zero detonator signal and test detonator's firing time. This method allows the timing for a number of detonators to be measured simultaneously, provided that the detonators have different delays, since separation of signals from individual detonators with the same delay is almost impossible. In principle, one electroacoustic sensor should be provided per detonator. The distance between each sensor and tested detonator should be the same. This is to eliminate the systematic error associated with different times of sound wave propagation in the cases of different distances between the sensor and the detonator. However, it is possible to use only one sensor when it is placed equidistant between both detonators. In this method, the sensor is connected directly to a computer equipped with sound wave recording software. The delay time is determined as the time difference (Δt) between the start pulse or a detonator with a zero delay and the tested detonator (Figure 1).

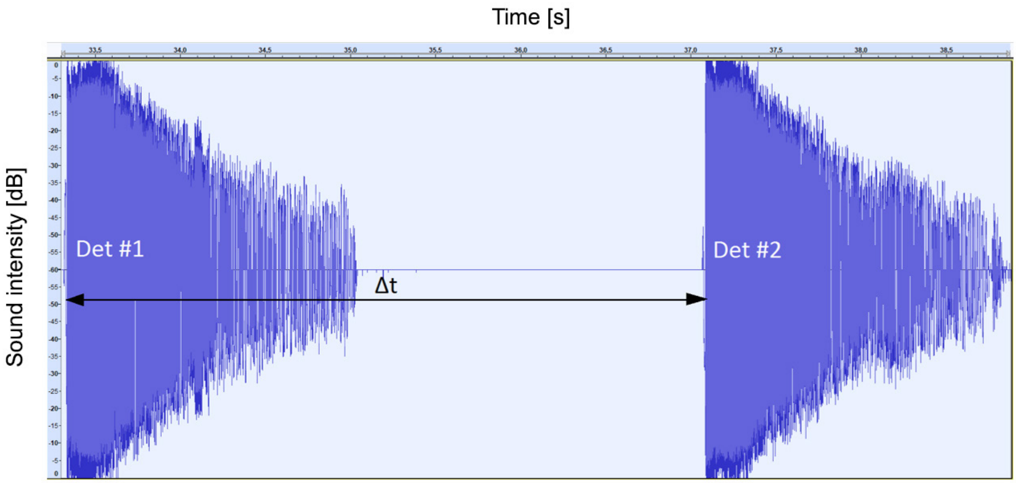


Figure 1. Delay time of detonator determined using an electroacoustic sensor

This method allows to determine the delay times of all types of detonators, i.e. electric, non-electric and electronic. The measuring accuracy depends primarily on the precise location of the detonator in relation to the sensor as well as on the sampling frequency of the sensor used.

3.2. Amplifier with an open-circuit probe

This system uses a measuring amplifier, an oscilloscope or a timer, to which open-circuit probes are connected. For this purpose, a test stand was designed, where the delay time between detonators is determined using a measuring amplifier. It records the voltage across a resistor in a simple electrical system including an open-circuit probe, attached to the detonator at the point of the base charge. Once the circuit is broken by the detonation, the voltage drops to zero. The delay time is determined from the plot and, as in the case of the electroacoustic sensor, is the time difference between the start pulse or the detonator with a zero delay and the tested detonator (Figure 2).

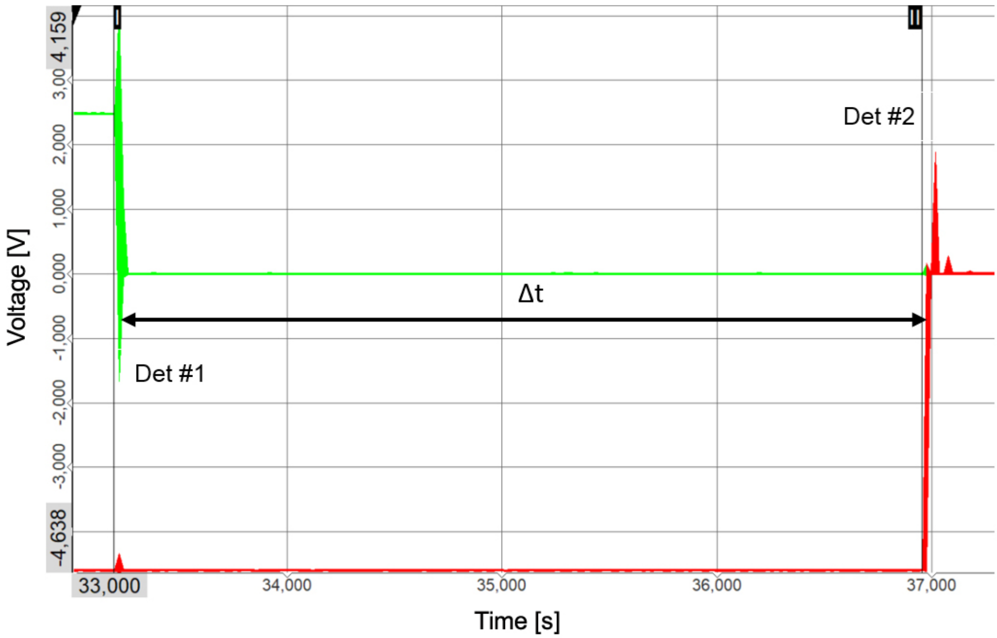


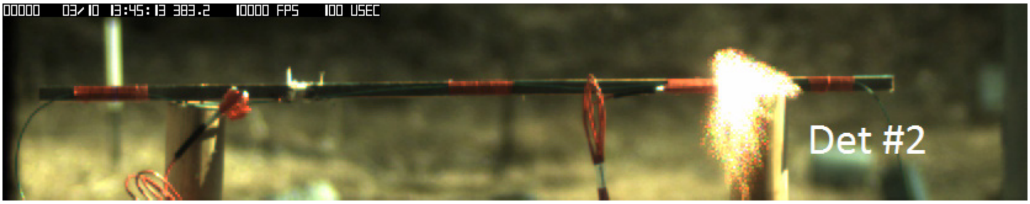
Figure 2. Delay time of detonator recorded using an open-circuit probe

This method allows the delay times to be determined for electric, non-electric and electronic detonators. In the case of non-electric detonators, optical sensors could be used for the start signal. This method is characterized by a high sampling frequency but is limited by the number of channels in the measuring amplifier. Another difficulty is the necessity of installing a thin probe to each detonator.

3.3. High-speed camera

An alternative method for determining the timing accuracy of detonators is a measurement based on images recorded using a high-speed camera. The recording signal may be triggered by the same start signal recorded by the measuring amplifier described in the previous method. The first recorded frame on which the flash from the detonation is observed indicates the delay time from the start signal triggering the camera. If the start signal is provided by the detonation of a detonator with a zero delay, then the delay time of the tested detonator is the time difference between the flashes from both the detonators (Figure 3).

(a)



(b)

Figure 3. Determination of delay time using a high-speed camera

Before the measurement, the camera should be secured in a place limiting the risk of its damage by the moving fragments of the cap shell. This method allows the delay times of all types of detonators to be determined. The number of simultaneously tested detonators is limited by both the camera's field of view and the size of its internal memory, which limits the maximum recording time. The appropriate placement of detonators even allows for simultaneous testing of several dozen detonators, even if they have the same delay time. The maximum recording time depends on the sampling rate and the size of the integrated internal memory. The delay time in this method is also determined as the time difference between the start pulse or zero delay detonator and the tested detonator.

3.4. Data recorder

The velocity of detonation (VOD) data recorder is another device which can be applied to determine detonator delay accuracy. Generally, such devices include all recorders for continuous measurements of VOD of explosives operating on the basis of a classic oscilloscope. Different types of probes with known unit resistance may be used in this system. During the test, the recorder measures the total probe resistance at high frequency. Firing the detonator results in the breaking or closing of the circuit, thereby changing its resistance. Consequently, the device records the value (decrease) of the circuit resistance at the moment of detonation. The delay time is determined graphically as the time increment between the start pulse or a detonator with a zero delay, and the detonator being tested (Figure 4).

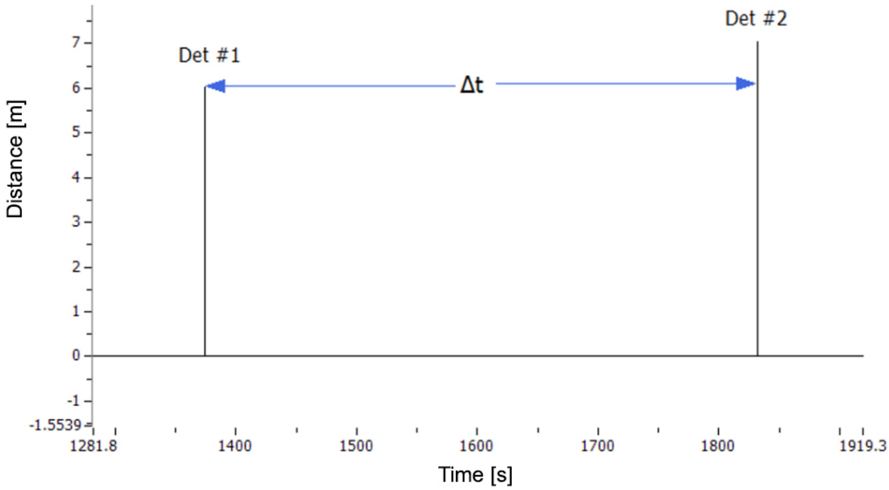


Figure 4. Determination of delay time of detonator using data recorder

Generally, there are no limitations to the number of detonators which can be tested simultaneously, using this method. For electric and electronic detonators, the only limitation is that they must be attached to the probe incrementally, i.e. starting with the shortest delay. This limitation does not apply to non-electric detonators connected in series, i.e. when the shock tube of the next detonator is attached to the previous detonator. In that case, the detonation of each detonator causes the initiation of the shock tube of the following detonator. When using such devices, the delay time can also be determined as the time difference between the start pulse or a zero delay detonator, and the detonator being tested. The maximum measuring time depends on the sampling rate and size of the internal memory.

3.5. Measuring system

The delay times of detonators may be determined using all the methods described above simultaneously on the same detonators. This allows potential errors or faults arising at the production stage to be eliminated, however these should not be found in electronic detonators, where the pyrotechnic delay is replaced with a very accurate electronic chip. Hence, the delay time of each detonator was determined using all four methods simultaneously. Therefore, the authors focused on identifying the most appropriate method for electronic detonator testing, rather than on verifying the accuracy of the programmed delay.
The start signal in all the systems can be triggered directly by the firing unit. However, considering that the ignition in electronic systems occurs with a different delay after the pulse is provided by the firing unit (depending on the system), two detonators were used in each test, one of which was programmed to a 0 ms delay and served as the start pulse. Thus, the delay time for a tested detonator was defined as the time difference between the ignition of both the detonators. The scheme of the measuring system is presented in Figure 5.

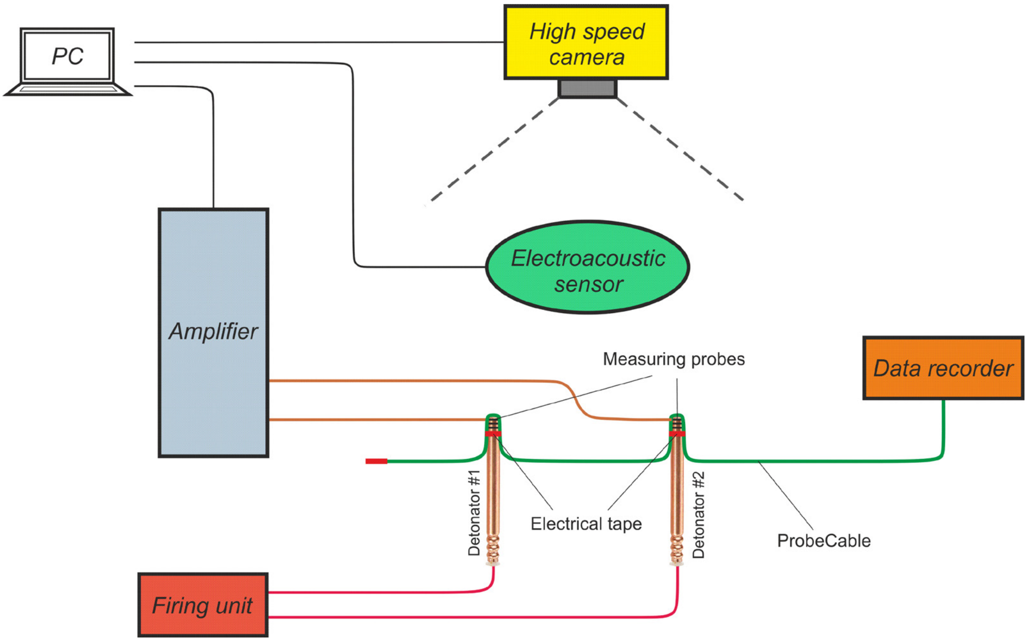


Figure 5. Schematic of the measuring system

During the test, each pair of detonators was taped to a wooden strip, at a distance of 500 mm from each other. A Tonsil's magnetoelectric W 66 microphone (electroacoustic sensor) was hung at the level of the detonators, at a distance of 1000 mm from each of them. The open-circuit probes of Dewesoft's SIRIUS HS amplifier and MREL's DataTrapII VOD recorder probe with a unit resistance of 10.8 Ω/m were taped to the detonator shells at the point of the base charge. A Mega Speed HHC X9 PRO camera was placed 3000 mm from the detonators' line. In order to protect the camera from fragments of the caps shells, it was additionally screened using an acrylic barrier. Data recorded by the electroacoustic sensor and amplifier were saved in the computer memory; in the case of the other methods – directly in the internal memories of devices. The sampling rate was 96 kHz for the electroacoustic sensor, 1 MHz for the measuring amplifier with an open-circuit probe, 10000 fps for the high-speed camera and 1 MHz for the data recorder.

4. Results and discussion

No misfires were observed during the tests, meaning that each of the 40 detonators ignited properly, indicating a 100% initiation efficiency. However, an analysis of the results showed that determining the delay time was not possible in 14 out of the 20 tests using VOD data recorder. This was because the firing time of both detonators was not recorded or only the initiation of the first one was recorded, indicating a 30% success rate for this method. As the moment of detonation is recorded only if both the shielding wire and the center conductor wire are broken or shorted, it was found that only the external (shielding) wire of the probe had broken in the 14 failed tests with the centre conductor remaining undamaged (Figure 6).

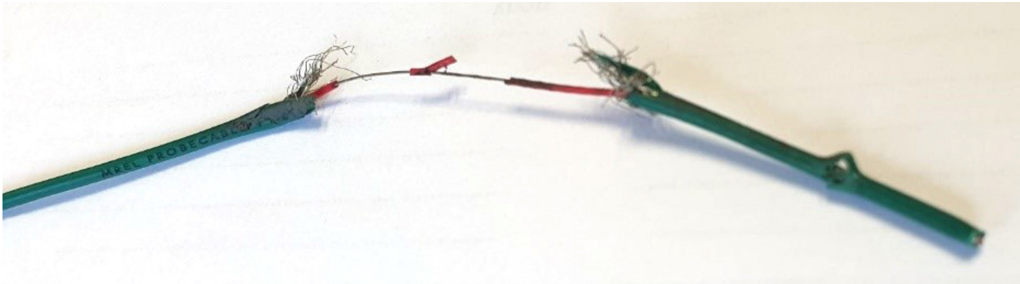


Figure 6. View of a probe after initiation of detonator

Based on the authors' experience in determining delay times of detonators using a data recorder in underground mines, it was assumed that the problem may result from the relatively low ambient temperature and, thereby, low temperature of the probes. Therefore, additional tests were conducted on 10 detonators. However, these were preceded by conditioning the probes in a climatic chamber at a temperature of 30 °C for 120 min. These measurements revealed a 100% success rate of recording, which indicates a limitation of this method. The results of the measurements are presented in Table 1. The last column shows the results of additional tests using the data recorder. For each method, the average value, standard deviation, minimum and maximum time and the difference between the minimum and maximum values, were determined.

The analysis indicates that the results obtained using the high-speed camera and the measuring amplifier with an open-circuit probe, are characterized by the lowest deviation from the average. These values were 0.1 ms for the high-speed camera and 0.102 ms for the amplifier. For the other methods, the deviation was 0.396 ms (0.344 ms) for the data recorder and 2.24 ms for the electroacoustic sensor. The smallest differences between the minimum and maximum values were obtained for measurements using the open-circuit probe and the high-speed camera. The highest, on the other hand were for the electroacoustic sensor (over 8 ms). The measurements are also presented in graphical form in Figures 7 and 8.

Table 1. Results of delay accuracy measurements (for a detonator programmed to 3750 ms)

Detonator no.	Time [ms]				
	Electroacoustic sensor	Open-circuit probe	High-speed camera	Data recorder	
				1-2 °C	30 °C
1	3746.30	3749.907	3749.9	error	3749.521
2	3754.38	3749.796	3749.8	error	3749.655
3	3747.25	3750.076	3750.1	3750.452	3750.155
4	3750.30	3750.040	3750.1	3750.533	3750.252
5	3747.32	3749.862	3749.9	3749.711	3750.060
6	3748.58	3749.890	3749.9	error	3749.753
7	3750.12	3749.897	3749.9	3750.325	3749.829
8	3748.77	3749.958	3749.9	error	3750.487
9	3749.61	3749.858	3749.8	error	3750.355
10	3750.18	3749.911	3750.0	error	3749.570
11	3752.47	3750.063	3750.0	error	–
12	3747.25	3750.103	3750.2	error	–
13	3751.71	3750.092	3750.0	3749.625	–
14	3752.13	3750.136	3750.2	error	–
15	3750.04	3750.103	3750.0	error	–
16	3747.41	3750.100	3750.0	error	–
17	3746.59	3749.950	3749.9	error	–
18	3751.30	3749.933	3750.0	error	–
19	3747.13	3750.036	3750.1	3750.373	–
20	3748.19	3749.947	3750.0	error	–
Average	3749.35	3749.983	3750.0	3750.170	3749.964
Deviation	2.24	0.102	0.1	0.396	0.344
Minimum time	3746.30	3749.796	3749.8	3749.625	3749.521
Maximum time	3754.38	3750.136	3750.2	3750.533	3750.487
Min–max	8.08	0.340	0.4	0.908	0.966

The closest results were obtained in those tests using the open-circuit probe and the high-speed camera. This is confirmed by the similar values of the average and deviation, as well as the non-outlier range for both the methods. It should be noted that when analyzing the results for individual detonators, the maximum difference between both methods is about 0.1 ms, which is most likely related to the lower resolution of measurements with the high-speed camera.

The greatest dispersion of the values obtained with other methods may be observed for the electroacoustic sensor. Even though the average delay time of 20 detonators is similar to those obtained using the measuring amplifier and the high-speed camera, the non-outlier range and the standard deviation indicate a significant spread. Furthermore, the results obtained with this method do not correlate with those of other methods. When analyzing the median and quartiles, it can be concluded that most of the observations are smaller than the average value.

The population of results obtained using the VOD data recorder is smaller compared to other methods due to difficulties in measurement. However, despite the smaller number of tests, one may conclude that this method is much more accurate than measuring with an electroacoustic sensor. In turn, compared to the high-speed camera and the open-circuit probe methods, the standard deviation is almost three times greater. The range of non-outliers for this method is 0.908 ms, which is significantly influenced by the problem related to the breaking or shorting of the probe wires. An additional series of 10 tests, at a higher ambient temperature, confirmed the observations obtained in the first series of tests conducted at lower temperature.

Also, in this case, the range of non-outliers and the standard deviation were very similar, just like the average value.

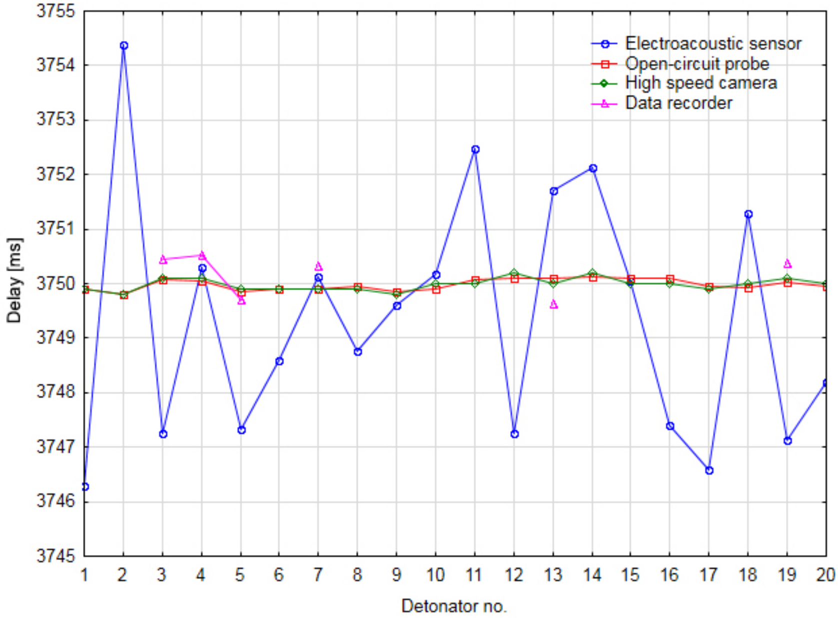


Figure 7. Results of timing accuracy measurements using different methods

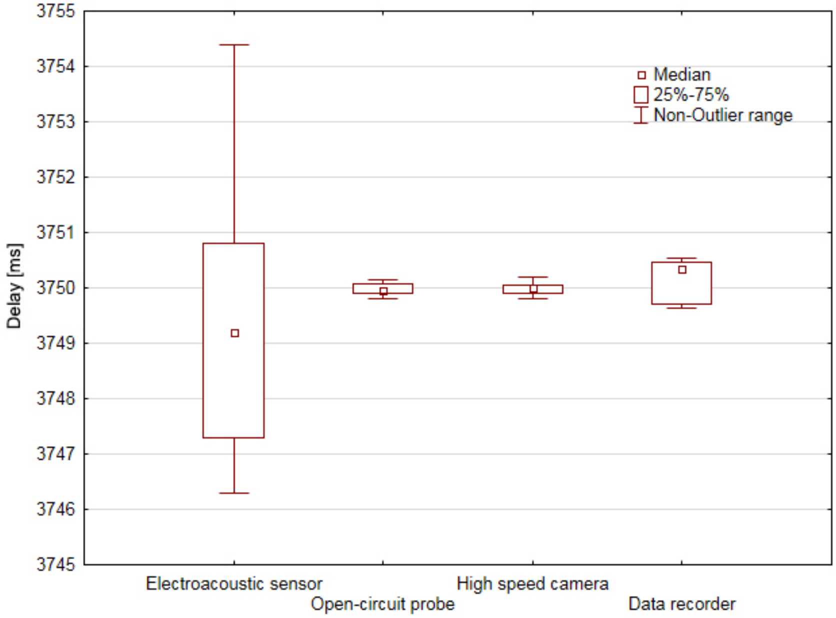


Figure 8. Statistical data presentation for selected values

Considering the costs of measurements, analysis should be carried out from the perspective of both the apparatus and the consumables. Tests using an electroacoustic sensor are the most favorable in terms of equipment costs. The price of such a sensor, depending on the manufacturer and operational parameters, usually ranges from 10 to 100 €. The more expensive the sensor, the faster the measurement stabilizes and the shorter the delay times which can be determined. The next device is the measuring amplifier which records data from the open-circuit probe. The cost of such an amplifier is between 5000-15000 € depending on the model. The VOD data recorder for continuous measurement of detonation velocity, depending on the manufacturer, size of internal memory and the sampling frequency will cost between 10000-30000 €. The most expensive device is the high-speed camera. Prices of such devices start from 15000 €, but those with a higher sampling rates can be appreciably more expensive.

When analyzing the costs of consumables, there are practically no such costs for two of the presented methods. These are the electroacoustic sensor and a high-speed camera methods. On the other hand, relatively low operating costs are associated with testing using the measuring amplifier, as the open-circuit probe cost per test does not exceed 1 €. The greatest costs per test is related to the VOD data recorder. Due to the nature of the measurement, testing of two detonators requires no less than 5 m of a probe. The cost of such a section of probe is about 5-7 €. A summary of the costs of individual methods is given in Table 2.

Table 2. Costs of timing accuracy measurements of detonators

Method	Costs [€]	
	equipment	consumables
Electroacoustic sensor	low: 10-100	very low
Open-circuit probe	medium: 5000-15000	low: <1
High-speed camera	very high: 15000-100000	very low
Data recorder	high: 10000-30000	high: 5-7

Taking into account the degree of difficulty of the measurements, the easiest procedure is associated with the high-speed camera, even though the data treatment is time consuming. The electroacoustic sensor method is the second most advantageous method in terms of difficulty. In this method, it is important to place the sensor exactly equidistant between the tested detonators. The difficulty increases as the number of detonators tested simultaneously increases. In the open-circuit probe method, it is necessary to wrap very thin wires around the detonators at the point of the base charge, and then connect them with communication wires to the amplifier. The tests using the VOD data recorder seem to be the most difficult. In this method, the probe must also be attached to the detonator at the point of the base charge, but both conductors of the coaxial probe must first be separated at the ends, so that they can be connected to the recorder at one end, and shorted on the other to complete the circuit.

According to the draft standard for the testing of electronic detonators, the results are considered correct if the value of $t_m \pm 3$ s for each analysed time remains within the range specified by the manufacturer. This means that for a delay of 3750 ms, the value of $t_m \pm 3$ s should be in the range from 3748.125 to 3751.875 ms. Therefore, it was found that the delay times determined using all the presented methods were correct, except for the electroacoustic sensor method. It should also be noted that the tests with an electroacoustic sensor, due to the relatively long stabilisation time of measurement (up to 1-2 s), are not suitable for determining short delay intervals in the presented configuration. This problem can be solved if the start pulse is provided directly by the firing unit.

5. Conclusions

- The methods presented in this paper enable the actual delay times of detonators to be estimated to reasonable degree. The results show that the methods of high-speed camera and open-circuit probes are characterized by the lowest standard deviation. Despite the fact that the sampling rate of the high-speed camera is only 10 kHz, the results for both methods coincide. In turn, the method with the electroacoustic sensor is characterized by a large spread and should not be used for determining the delay accuracy of electronic detonators. The large spread of results was obtained despite precise placement of the detonators in relation to the sensor. Alternatively, for future work the application of more precise electroacoustic sensors could be considered. Results obtained using the data recorder indicate that this method is sufficiently accurate for testing electronic detonators. However, increasing the sampling rate should be considered to improve the precision. The tests also revealed the negative influence of low temperatures on probes, and thus on the effectiveness of measurements.
- The analysis confirmed that electronic detonators are characterized by a very high delay accuracy. The measured differences in the delay times are minor. They can even be considered insignificant from the mining point of view. This indicates that the order of magnitude of the measuring accuracy should not be the main factor determining the selection of a given method. It should rather be based on the degree of difficulty of the method and the maximum number of detonators which can be tested in a single test. From this perspective, the measurements using the high-speed camera and the data recorder proved to be the most efficient.
- The last factor which should be considered is the possibility of detonator testing directly at the mine. For this purpose, both the high-speed camera and the data recorder may be used, however the tests using the camera would be limited to locations where the influence of shards is reduced. Of course, there is also the possibility of determining delay times of detonators in-situ with other methods, but this would require ensuring the appropriate testing infrastructure. Considering the relatively simple test procedure, the method with the VOD data recorder seems to be the optimal one for in-situ measurements, but also for other qualitative testing where overlapping of delay time of detonators is unacceptable.

Acknowledgements

This paper has been prepared under the statutory research of the Central Mining Institute, work number 11332028.

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Received: May 10, 2021
Revised: October 8, 2021
First published online: October 29, 2021