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INCREASING MEASUREMENT ACCURACY IN ELECTRO-OPTICAL METHOD FOR MEASURING VELOCITY OF DETONATION

POVEĆANJE TOČNOSTI ELEKTROOPTIČKE METODE ZA MJERENJE BRZINE DETONACIJE

MARIO DOBRILOVIĆ, VJEČISLAV BOHANEK, VINKO ŠKRLEC

Sveučilište u Zagrebu, Rudarsko-geološko-naftni fakultet, Pierottijeva 6, p.p. 390, 10000 Zagreb.

Ključne riječi: Brzina detonacije, elektro-optička metoda, mjerna nesigurnost

Sažetak

U odnosu na ostale parametre detonacije, brzina detonacije je veličina koja pruža neizravne podatke o snazi odnosno brizantnosti eksploziva i djelovanju eksploziva. Osim toga, brzina detonacije se u usporedbi s drugim detonacijskim parametrima, može mjeriti na relativno jednostavan i precizan način, pomoću razvijenih i dostupnih metoda. Zbog jednostavnosti upotrebe, kompaktnih instrumenta i zadovoljavajuće točnosti, elektro-optička metoda mjerenja brzine detonacije se često koristi.

U radu je opisana elektro-optičku metoda mjerenja brzine detonacije s analizom čimbenika koji utječu na točnost metode. Prema rezultatima analize mjerenih podataka primjenom različitih mjernih postava povećana je točnost elektrooptičke metode sa smanjenjem iznosa mjerne nesigurnosti

Key words: Velocity of detonation, electro-optical method, measurement uncertainty

Abstract

In addition to other detonation parameters detonation velocity is a value that provides indirect information on the strength i.e. brisance of an explosive and explosive performance. In addition to that, detonation velocity is a value which can be measured in a relatively simpler and more precise manner, by developed and accessible methods when compared to other detonation parameters Due to its simple use, compact instruments and satisfactory accuracy, electro-optical method of detonation velocity measurement is widely used.

The paper describes the electro-optical measurement method and points out the factors that affect its accuracy. The accuracy of measurement is increased and measurement uncertainty is reduced by the measurement result analysis with the application of different measurement setups.

1. Introdution

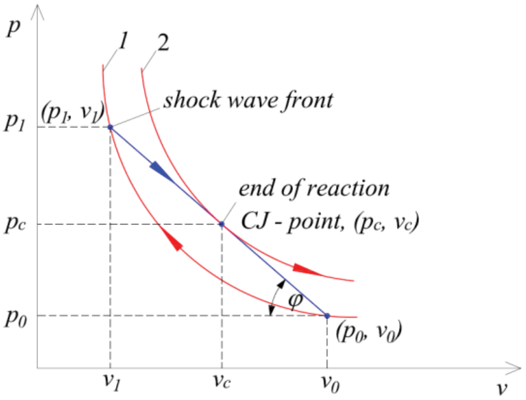
Explosives are chemical substances that can release thermal energy through a very rapid, exothermic oxidation, which can be used in the form of useful work in the media where explosion occurs. In relation to that, explosives are high energy materials and according to their chemical composition they are either mono-molecular compounds or mixtures of explosive or non-explosive components. Physical parameters of an explosion in the form of detonation or explosive combustion depend primarily on chemical composition, i.e. properties of an explosive substance. In addition to other detonation parameters (detonation heat, detonation pressure, volume of detonation gaseous products, oxygen balance and detonation temperature), detonation velocity is a value that provides indirect information on the strength i.e. brisance of an explosive. It is a value which should be known for the synthesis of new explosives, as well as during the production quality control, placing on the market and supervision of explosives.

In addition to that, detonation velocity is a value which can be measured in a simpler and more precise manner, by developed and accessible methods when compared to other detonation parameters (Sućeska, 1995).

The detonation velocity can be measured by relatively simpler methods that can be applied to samples in laboratory, field and in actual boreholes. Generally, measurement methods for detonation velocity can be divided, according to the measurement principle, into continuous and discontinuous methods. According to the measured value and conversion of a signal they are divided into electrical, optical and electro-optical methods.

2. Velocity of Detonation

By detonating the explosive charge the explosive passes from the initial, mostly solid to gaseous form. Chemical reactions that follow the shock wave front occur within nanoseconds. The detonation front moves at the detonation speed in the opposite direction of the place of initiation. The state of an explosive during adiabatic compression by the shock wave, chemical changes in detonation wave and expansion of detonation gaseous products is described by the classical hydrodynamic theory, i.e. ZND model. The state of an explosive during detonation is described according to Rankine Hugoinot equations derived from the conservation laws of mass, momentum, and energy during adiabatic compression of explosive substance (Sućeska, 1997). According to the aforementioned theory the points in p-v diagram of a shock adiabatic curve of the compressed explosive matter can be related to Rayleigh line which is the tangent line of the adiabatic curve of the products of detonation in the point marked by CJ. It represents the state of an explosive at the moment when chemical reactions are completed, i.e. the state of explosive substance after the reaction. In this case, the points lying on that line represent the state of the undisturbed explosive substance before the reaction, maximally compressed in the shock wave front, and the state of gaseous product after completed reaction, immediately before the adiabatic expansion. Its slope is determined by the velocity of stable and ideal detonation of an explosive substance. The detonation process in p-v diagram is shown in Figure 1.



Index:

φ – angle of inclination of Rayleigh line (°),
p_o – initial pressure (Pa),
p_o – maximum pressure (Pa),
p_c – pressure in CJ point (Pa),
v_0 – initial volume, specific volume (m^3, m^3/kg),
v_1 – maximum volume, specific volume (m^3, m^3/kg),
v_c – volume, specific volume in CJ point (m^3, m^3/kg),
1 – shock adiabatic curve,
2 – adiabatic curve of explosion products,
3 – Rayleigh line,
→ – direction of the detonation process

Figure 1. Detonation process in p-v diagram

Slika 1. *Detonacijski process u p-v dijagramu*

The slope of Rayleigh line in p-v diagram is defined by the tangent of the angle between Rayleigh line and x axis. After the completion of chemical reactions, or after CJ point, the expansion of gaseous product begins and the detonation is completed. By combining equations of conservation of mass and momentum the equation for Rayleigh line is derived:

$$\frac{p_1 - p_0}{v_1 - v_0} = -\rho_0^2 D^2 \qquad (1)$$

where:

p_0 - pressure in undisturbed explosive substance (Pa),
p_1 - shock wave pressure (Pa).
v_0 - specific volume of undisturbed substance (m^3/kg),
v_1 - specific volume of substance compressed by shock wave (kg/m^3)
ρ_0 - density of initial undisturbed explosive substance (kg/m^3)
D - shock wave velocity (m/s),

The velocity of detonation process is defined by the slope of Rayleigh line, i. e. the angle between Rayleigh line and x axis of the p-v diagram by equation (2).

$$\tan\varphi = \frac{p_1 - p_0}{v_0 - v_1} = \rho_0^2 D^2 \qquad (2)$$

As the line is a tangent line of the adiabatic curve of explosion products, the equation (3) is valid:

$$\tan\varphi = \left(\frac{dp}{dv}\right)_{CJ} \qquad (3)$$

The state and detonation parameters of explosive substances can be calculated by equations and models, i.e. programmes which use equations for chemical balance and known values of parameters to estimate detonation parameters. Models provide satisfactory values of estimated parameters but it is necessary to conduct empirical verification and evaluation of the parameters. Since those processes are exceedingly rapid with extreme values of physical properties, measuring certain parameters presents serious problems.

The values of the pressures of the detonation process, which are also dependent on the detonation velocity, are relevant for the impact on the rock in the surroundings of the borehole. The detonation pressure can be generally linked to the detonation velocity according to the eguation (4):

$$p = \frac{\rho_0 D^2}{4} \qquad (4)$$

where:

p - detonation pressure (Pa),
ρ_0 - density of explosive substance (kg/m^3),
D - velocity of detonation (m/s)

3. Subject and Methods

The procedure of velocity detonation measurement for explosives for civil uses is determined by EN 13631-14:2003 standard (CEN, 2003). The standard does not prescribe the application of a measurement method, but it prescribes the way of measurement, measurement setup, initiating devices and measurement sensors. Taking into account the initial stability of the detonation process in the vicinity of the initiating device, the minimum distance to the nearest sensor is determined in order to measure stable, constant velocity of detonation.

Due to its simple use, compact instruments and satisfactory accuracy, electro-optical method of detonation velocity measurement is widely used.

Electro-optical method is based on the precise time measurement by the electronic timer. It is a discontinuous method, since the average time, i.e. detonation velocity, is measured on individual length segments. If more channels are used, the average velocity on more segments can be measured, but it is not possible to measure the distribution of velocity within one segment. A time segment is defined by the times of receiving light signals transmitted by optical cables from the zone of the arrival of the detonation wave. Since the detonation wave is luminous, as it passes between optical cables the time difference between two light signals is achieved. Therefore, the detonation velocity is calculated according to the equation:

$$D = \frac{l}{t} \qquad (5)$$

where:
D - velocity of detonation (m/s),
l - distance between optical cables (m),
t - time difference between the signals transmitted by optical cables (s)

By applying the electro-optical method of velocity detonation measurement for explosives for civil uses several groups of factors that influence measurement accuracy and uncertainty were identified. Those are:

- applied method and corresponding measuring equipment,
- type of the explosive substance,
- accuracy of the measurement setup for the applied method.

Detonation velocity of an explosive substance with a defined chemical composition, physical properties and diameter of a charge is generally constant.

The properties of the explosive substance, when the conditions of achieving stable detonation are fulfilled, influence measurement uncertainty through consistency and non-homogeneity of explosives on the level of cartridge or charges of the free flowing explosives in steel testing pipes. The example of that impact is visible that, while filling the testing pipe with free flowing explosive it is difficult to achieve the same density of the charge, which directly affects detonation velocity.

The usual discontinuous methods of velocity of detonation measurement imply the use of either optical or electrical cables for detecting the arrival of detonation wave. Since the sensors are placed within the cartridge or the testing pipe, mostly at the half of diameter of the cartridge or the testing pipe, the error in the distance between the sensors is possible. The second cause of the error is the accuracy in determining, i.e. measuring the distance between sensors and transmitting the distance onto the cartridge or the testing pipe.

In order to measure detonation velocity a measuring instrument “Explomet-Fo-2000” was used. It is an electronic timer for which measuring is initiated and stopped by light signals. The highest velocity that can be measured is 10000 m/s, and time intervals between 0.1 µs and 10000 µs with the accuracy of ± 0.1 µs according to the manufacturer’s declaration.“Explomet-Fo-2000” is presented in Figure 4.

Figure 2. Electronic timer “Explomet-Fo-2000”

Slika 2. *Elektoronički sat “Explomet-Fo-2000”*

Detonation velocity measurement was carried out on the samples of ANFO in steel pipes. Testing samples were adapted to laboratory conditions in relation to the pipe diameter and the mass of the explosive.

Previously, when a large number of measurements were carried out during certification and control of the properties of ANFO, considerable deviations in measurement results were recorded. Therefore, ANFO was used for the aforementioned research for determining the impact of the measurement method and the possibility of improvement.

The tested samples of ANFO, for which the velocity of detonation was measured, were initiated by

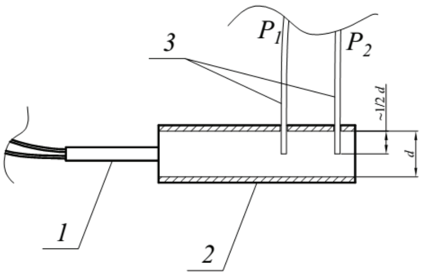
40 °C). Ammonium nitrate / fuel oil ratio was 94.6 % of ammonium

3.1. Measurement setup

Measurements of detonation velocity with the purpose of improving measurement setting in order to reduce measurement uncertainty of the electro-optical method were conducted with three different measurement settings of sensors on samples of ANFO in steel pipes.

Measurements were carried out on the samples in steel pipes of the following dimensions: length 150 mm, outer diameter 27.5 mm, inner diameter 23.5 mm, while the mass of ANFO was approximately 50 g. Targeted distance between the sensors (P1-P2) was 40 mm, and the first sensor was installed at the distance of 90 mm from the place of initiation. The samples are initiated by electric detonators. Before the sensors were installed in holes, the axial distance between the holes was measured. Ten samples were detonated for each measurement setup.

Individual setups of sensors are presented in Figures from 3 to 5.



where:

1 – electric detonator,
2 – steel pipe with testing sample,
3 – sensors (optical cables),
P_1- first probe,
P_2- second probe,
d – inner diameter of pipe (mm).

Figure 3. Measurement setup I

***Slika 3.** Mjerni postav I*

The 1st measurement setting of sensors is based on installing sensors in a steel pipe, filled by ANFO, at the depth of approximately 1/2 of the inner diameter of the pipe vertically to the direction of the detonation wave expansion.

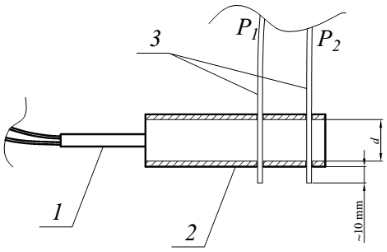


Figure 4. Measurement setup II

***Slika 4.** Mjerni postav II*

The 2nd measurement setting of sensors is based on installing sensors through the whole diameter of a steel pipe, filled by ANFO, vertically to the direction of the detonation wave propagation in the way that sensors extend to the other part of the pipe, approximately 10 mm.

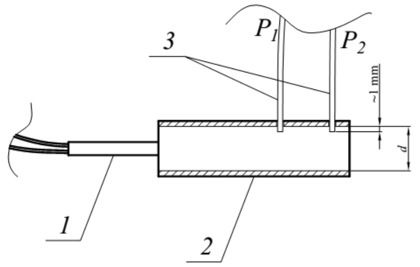


Figure 5. Measurement setup III

***Slika 5.** Mjerni postav IIi*

The 3rd measurement setting of sensors is based on installing sensors in a steel pipe, filled by ANFO, at a depth of approximately 1 mm of the borehole wall, vertically to the direction of the detonation wave expansion.

4. Results

The measurement results of time, distance between holes and corresponding detonation velocity of ANFO for each measurement setup are presented in Tables 2 - 4.

Table 1. Measured results, setup I

***Tablica 1.** Rezultati mjerenja, postav I*

Measurement No.	Measured time (µs)	Distance *P1-P2* (mm)	*D* (m/s)
1	38.7	42.63	1101
2	33.9	41.03	1210
3	28.3	39.23	1386
4	28.7	41.02	1429
5	32.5	36.85	1134
6	43.1	40.04	929
7	34.7	37.40	1078
8	38.5	39.19	1018
9	42.2	39.73	941
10	38.3	41.65	1087

Table 2. Measured results, setup II

***Tablica 2.** Rezultati mjerenja, postav II*

Measurement No.	Measured time (µs)	Distance *P1-P2* (mm)	*D* (m/s)
1	41.4	42.31	1022
2	38.6	39.67	1028
3	34.1	41.12	1206
4	36.6	39.25	1072
5	40.2	38.65	961
6	34.4	40.67	1182
7	39.2	38.91	992
8	38.7	40.59	1049
9	35.9	38.80	1081
10	39.9	40.88	1024

Table 3. Measured results, setup III

Tablica 3. *Rezultati mjerenja, postav III*

Measurement No.	Measured time (μs)	Distance *P1-P2* (mm)	*D* (m/s)
1	40.2	40.41	1005
2	43.1	41.23	956
3	43.2	40.41	935
4	42.3	39.69	938
5	41.0	39.78	970
6	39.0	40.71	1044
7	39.4	40.60	1030
8	42.4	40.08	945
9	38.5	40.63	1055
10	42.2	40.05	949

Measurement results show the highest deviation for the 1st measurement setup with the largest difference between maximum and minimum detonation velocity of 500 m/s. The difference for the 2nd measurement setup was 245 m/s, and the most balanced measurement results were obtained for the 3rd setup with the difference of 120 m/s.

The graphical representation of the average, minimum and maximum values of measured detonation velocities for individual setup are given in Figure 6.

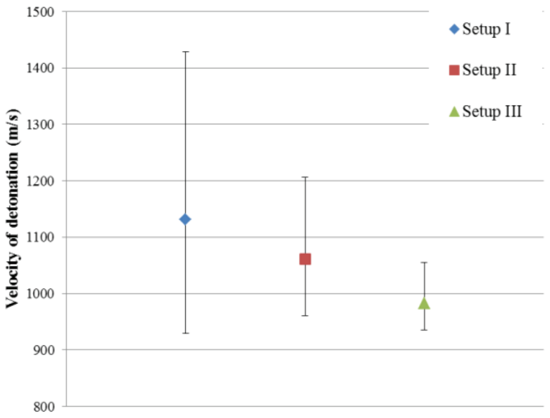


Figure 6. Average, minimum and maximum values of measured detonation velocities

Slika 6. *Prosječne, minimalne i maksimalne izmjerene vrijednosti brzina detonacije*

5. Discussion

With the constant measurement conditions and explosive substance, the accuracy of time measurement and measurement of distance between the sensors influence the measurement result. The impact of time measurement is determined by the accuracy of the applied measuring instrument, i.e. electronic timer Explomet-Fo.

The accuracy of distance between the sensors, while measuring detonation velocity of the samples in steel pipes, is determined by precise drilling of holes in the pipe and diameter of the hole within which the optical cable can be moved within the axis of the pipe. The impact of accuracy of the hole axis distance is eliminated by measuring real distance by a caliper, while the value of distance is affected by measuring uncertainty of length measurement by a caliper which equals 0.05 mm and it is included in the error limit of the individual setup. The impact of accuracy of hole distance is schematically shown in Figure 7.

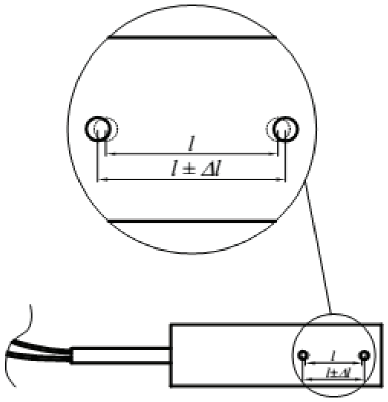


Figure 7. The impact of accuracy of hole distance

Slika 7. *Utjecaj točnosti udaljenosti između provrta*

The impact of the difference between hole diameter and sensor diameter equals 0.5 mm and it is included in the error limit of all setups. The difference between diameters, in the case of the 1st measurement setup, additionally affects the value of the possible shift of sensors, taking into consideration the largest angle of inclination with the defined thickness of the pipe wall. The possible shift of sensors is schematically shown in Figure 8.

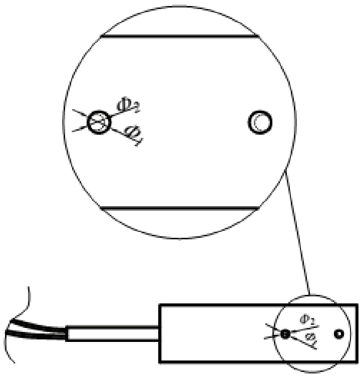


Figure 8. Possible shift of sensors in relation to hole diameter

Slika 8. *Moguće pomicanje osjetila u odnosu na promjer promjera provrta*

By modifying the 1st, 2nd and 3rd measurement setup a possible deviation of optical cables in relation to targeted distance was limited. The possible deviation was the largest for the 1st setup due to possibility of inclined position of sensors in relation to vertical line on the pipe axis and flexibility of the sensor, and error limit is estimated to ±8 mm.

By installing an optical cable through the pipe the impact of inclined position of the cable is eliminated and the possibility of bending of cables is reduced. In that case, the estimated error limit is ±4 mm.

The 3rd setup eliminates the possibility of bending of sensors and error limits are reduced to the value of the possible error in the distance caused by the inclined position of sensors resulting in deviation in the pipe axis, with error limits of ±2 mm. Errors in installing sensors are schematically shown in Figures 9-11.

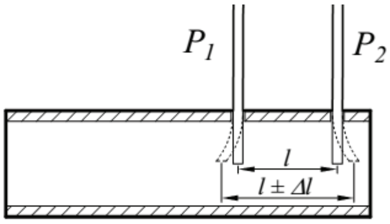


Figure 9. Displacement in installing sensors, setup I

Slika 9. *Pomak pri postavljanju osjetila, postav I*

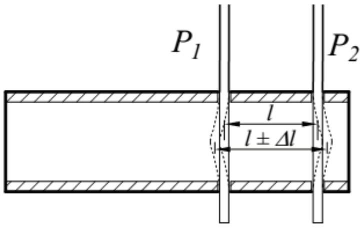


Figure 10. Displacement in installing sensors, setup II

Slika 10. *Pomak pri postavljanju osjetila, postav II*

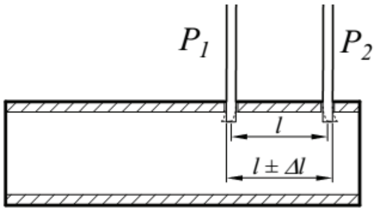


Figure 11. Displacement in installing sensors, setup III

Slika 11. *Pomak pri postavljanju osjetila, postav III*

Measurement uncertainty calculation was conducted for all three setups. While calculating measurement uncertainty, two most important factors were taken into consideration: error in the distance between sensors, and accuracy error of the measuring instrument. Data on the measuring instrument accuracy were taken from manufacturer's declaration and error limits of the distances between optical cables were estimated.

Combined standard uncertainty $u_c(D)$ is calculated according to EA 4/02 (EA, 2013) for the case where two quantities are not correlated. The combined standard uncertainty $u_c(D)$ is the positive square root of the combined variance which is given by the equation (6).

$$u_c^2(D) = \sum_{i=1}^{n} c_i^{\,2} u^2(x_i) \tag{6}$$

Sensitivity coefficients c_1 and c_2 can be calculated according to the equations (7) and (8):

$$c_1^2 = \left(\frac{\partial D}{\partial l}\right)^2 = \left(\frac{1}{t}\right)^2 \tag{7}$$

$$c_2^2 = \left(\frac{\partial D}{\partial t}\right)^2 = \left(\frac{-l}{t^2}\right)^2 \tag{8}$$

This leads to eguation (9):

$$u_c(D) = \sqrt{\left[\left(\frac{1}{t}\right)u_c(l)\right]^2 + \left[\left(\frac{-l}{t^2}\right)u_c(t)\right]^2} \tag{9}$$

Expanded measurement uncertainty U is calculated according to the equation (10):

$$U = ku_c(D) \tag{10}$$

For the case where two rectangular distributions are convolved, the coverage factor k for a coverage probability of 95.45% is obtained from M3003 (UKAS, 2012)

Calculated measurement uncertainties are shown in Tables 4-6.

Table 4. Measurement uncertainty, setup I,

Tablica 4. *Mjerna nesigurnost, postav I*

Quantity	Estimate	Error limit	Standard uncertainty $u(x_i)$	Probabillity distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(v)$
Lenght (l)	0.04 m	± 8 mm	4.6188 mm	rectangular	27942.72 s^{-1}	129 m/s
Time (t)	35.79 µs	± 0.1 µs	0.0577 µs	rectangular	31231818 m/s^2	1.8 m/s
Velocity (D)	1131 m/s				**$u_c(D)$ =**	**129 m/s**
			***k*=** 1.65		***U*$_{95}$=**	**213 m/s**

Table 5. Measurement uncertainty, setup II,

Tablica 5. *Mjerna nesigurnost, postav II*

Quantity	Estimate	Error limit	Standard uncertainty $u(x_i)$	Probabillity distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(v)$
Lenght (l)	0.04 m	± 4 mm	2.3094 mm	rectangular	26385.22 s^{-1}	60.9 m/s
Time (t)	37.90 µs	± 0.1 µs	0.0577 µs	rectangular	27847202 m/s^2	1.61 m/s
Velocity (D)	1062 m/s				$\boldsymbol{u_c(D)}$ **=**	**61 m/s**
			***k*=** 1.65		$\boldsymbol{U_{95}}$**=**	**100 m/s**

Table 6. Measurement uncertainty, setup III,

Tablica 6. *Mjerna nesigurnost, postav III*

Quantity	Estimate	Error limit	Standard uncertainty $u(x_i)$	Probabillity distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(v)$
Lenght (l)	0.04 m	± 2 mm	1.1547 mm	rectangular	24313.15 s^{-1}	28.1 m/s
Time (t)	41.13 µs	± 0.1 µs	0.0577 µs	rectangular	23645177 m/s^2	1.37 m/s
Velocity (D)	982.9 m/s				$\boldsymbol{u_c(D)}$ **=**	**28.1 m/s**
			***k*=** 1.65		$\boldsymbol{U_{95}}$**=**	**46 m/s**

Measurement uncertainty calculation shows that a measurement setup, i.e. the way of installing sensors has the largest impact on the value of measurement uncertainty. Length and time contribution to measurement uncertainty is shown in Figure 9.

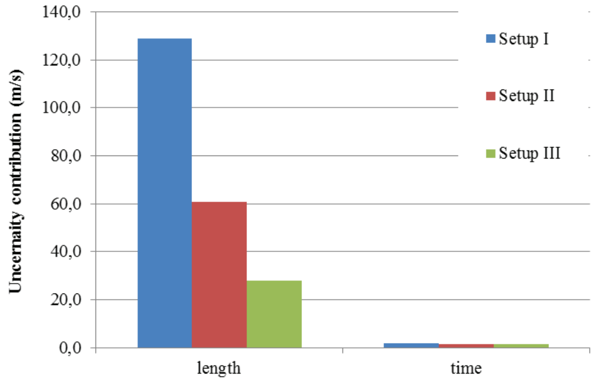


Figure 12. Contribution of the uncertainty of the length and time to measurement uncertainty velocity of detonation

Slika 12. *Doprinos nesigurnosti duljine i vremena mjernoj nesigurnosti brzini detonacije*

6. Conclusion

Aforementioned measurements and measurement data analysis show that, while measuring detonation velocity, a range of possible values determined by measurement uncertainty can be reduced four times by applying appropriate measurement setup. In that case measurement uncertainty is substantially reduced. Measurement uncertainty assessment that was carried out was in accordance with measurement result and it can be concluded that the impact of individual factors on measurement result accuracy was determined correctly. Since usual measurements are carried out on samples of higher detonation velocity, at larger distances between sensors with the same error limits of the method, the application of the 3rd measurement setup provides substantial improvement in accuracy of detonation velocity measurement by electro-optical method.

The measurement results that are presented in the paper can be applied to detonation velocity measurements of civil and military explosives. They can also be used in the research of new explosives when it is necessary to measure detonation velocity accurately and when measurements are carried out on samples of smaller dimensions which results in high measurement uncertainty due to the measurement setup of probes.

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