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Marek Dźwiarek<sup>a</sup>

<sup>a</sup> Central Institute for Labour Protection, Poland

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# Measurement Accuracy of the Electrosensitive Protective Device Response Time When Using the Double Penetration Method

Marek Dźwiarek

Central Institute for Labour Protection, Poland

The Double Penetration Method (DPM) method of measuring ESPD (Electrosensitive Protective Device) response time was presented by Dźwiarek (1997). Calibrating the measuring equipment is a crucial stage of the procedure. Experimental verification of theoretical predictions is also crucial. For calibration purposes, a device simulating real ESPD operation thus enabling a correct setting of the response time was designed (Dźwiarek, 1997).

Theoretical analysis has shown that measuring ESPD response time with the DPM is subject to localisation errors made in the localisation of the detection zone border, rod position measurement errors made during high-speed penetration, and time delay measurement errors. The values of all those components of the total error have been determined experimentally using the calibrating device. Measurements have been taken under conditions as close to real ones as possible proving that the total measurement error is really enclosed within the assumed limits.

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safety safety of machinery Electrosensitive Protective Devices  
certification testing

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## 1. INTRODUCTION

Dźwiarek (1997) presented an original method for Electrosensitive Protective Device (ESPD) response time measurement, in which the detection zone was penetrated twice (Double Penetration Method [DPM]). The first penetration, made at a low speed, enables the

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Correspondence and requests for reprints should be sent to M. Dźwiarek, Central Institute for Labour Protection, ul. Czerniakowska 16, 00-701 Warszawa, Poland. E-mail: <madzw@ciop.waw.pl>.

detection zone border to be localised, whereas the second, high-speed, penetration allows the measurement of response time. The measurement procedure consists in utilising a known position of the detection zone border and monitoring the current state of output relays. A special SBUO1 experimental stand was built (Dźwiarek, 1995) enabling the DPM measurements to be taken. The main sources of measurement errors can be detected from the analysis of the measurement procedure realised on this stand. The total measuring accuracy is influenced by the effects appearing during both penetrations. After determining all components of the measurement error, total accuracy is estimated theoretically.

One of the crucial stages of the measurement procedure consists in calibrating the measuring equipment (International Organization for Standardization and International Electrotechnical Commission, 1997; Polski Komitet Normalizacyjny, 1995). When the DPM is used, experimental verification of theoretical predictions is also of crucial importance. At the Central Institute for Labour Protection (Poland) experimental verification of the real measurement error has been performed. The checking-calibration procedures of the measurement stand have also been established (Dźwiarek, 1995).

## 2. CALIBRATING DEVICE

To calibrate the SBUO1, it was necessary to design a device that could simulate the operation of a real Electrosensitive Protective Device, enabling at the same time a correct setting of the response time. This device would then allow experimental determination of all components of the measurement error.

### 2.1. Description of the Device

Figure 1 shows the calibrating device. As a light curtain is the most typical Electrosensitive Protective Device, the detection zone is simulated with a light beam. For calibration, the device can be mounted on the SBUO1 stand.

The device consists of three modules: (a) optical, (b) mechanical, and (c) electronic. The beam stop with gaps, which can be seen in Figure 1, is not used in the course of the measurements, having been mounted for demonstration purposes only. A metal plate plays the role of a beam stop.

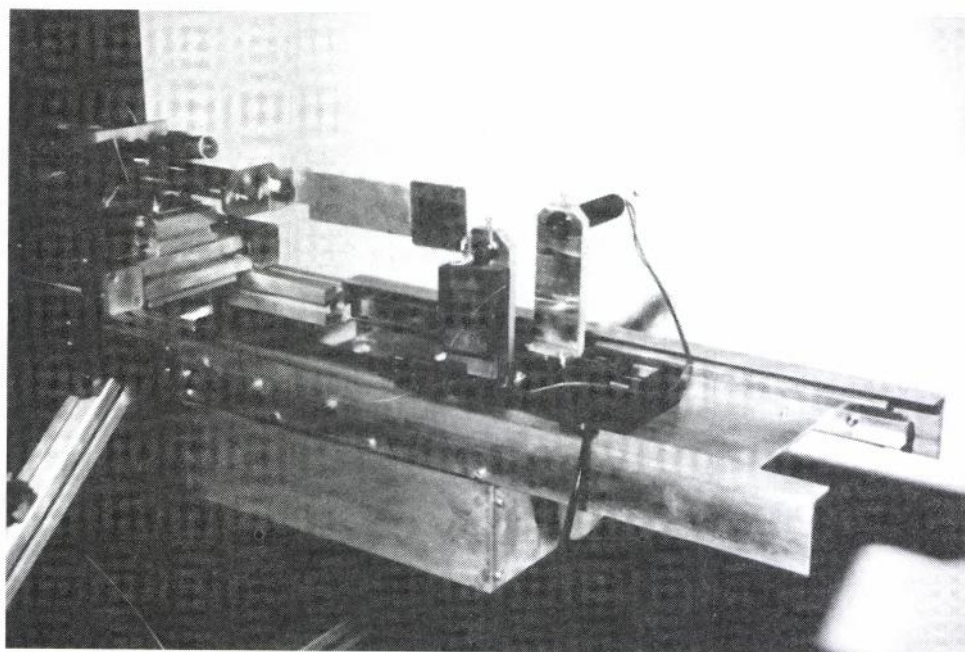


Figure 1. A calibrating device mounted on the SBU01 stand.

### 2.1.1. Optical module

The optical module enables simulation of the detection zone. It consists of a light beam transmitter and a receiver. Localising the detection zone border is crucial for the measurement process. To minimise errors resulting from the optical system, a semiconductor laser is used to generate the light beam. A laser of this type makes it possible to change the narrowing width by adjusting the position of the focusing lens. It is possible to obtain a narrowing width of less than  $50\ \mu\text{m}$ . However, for our purposes, a narrowing width of less than  $100\ \mu\text{m}$  is satisfactory. The diffraction effect is used to control the narrowing width. If the light beam passes through a gap whose diameter is greater than its own, a light spot appears on the screen located behind the gap. If the beam diameter is greater than that of the gap, diffraction rings appear. A set of standard gaps was created to control the diameter of the light beam. The gap widths measured with an electron microscope are  $100 \pm 10\ \mu\text{m}$ ,  $150 \pm 10\ \mu\text{m}$ ,  $200 \pm 10\ \mu\text{m}$ ,  $300 \pm 10\ \mu\text{m}$ , and  $400 \pm 10\ \mu\text{m}$ .

A photodiode plays the role of a light signal receiver. It generates a signal transmitted to the electrical module informing whether the light

beam has been stopped. It has been experimentally verified that the signal coming from the diode changes its level if the actuator translates about  $10\ \mu\text{m}$  at a narrowing width of less than  $100\ \mu\text{m}$ . Such a detection zone simulation procedure ensures an accuracy of the localisation of the detection zone border of  $\pm 10\ \mu\text{m}$ .

### *2.1.2. Mechanical module*

The mechanical system provides precise positioning of the optical system relative to the main actuator of the SBUO1 stand. It is realised by means of a two-step translation procedure. Displacement of the optical system is realised by a screw of a micrometric table on which the system is mounted. That also ensures a readout of the displacement value. The table is fixed to a platform mounted on the frame of the SBUO1 stand by means of a ball slide system. Displacement of the platform is realised by means of a precise guide screw with a grinded thread.

The screw is supplied with a clearance erasing system. An electronic length meter made by VIS (Poland) is mounted on the platform. The meter's sliding head is fixed to the movable part of the micrometric table. The length meter provides displacement readout accuracy of  $\pm 0.005\ \text{mm}$ . The guide screw provides rough positioning, whereas the micrometric table ensures precise positioning.

Both the platform and the table can be moved along the distance of  $225\ \text{mm}$ . This design has positioning accuracy of  $\pm 10\ \mu\text{m}$ . The total accuracy of detection zone border localisation, after taking into account the optical module accuracy, is  $\pm 20\ \mu\text{m}$ . The obtained accuracy is, therefore, several times better than that of the measuring system to be calibrated.

### *2.1.3. Electronic module*

The electronic module should detect a signal from the photodiode and, at a given time after the light beam has been crossed, generate a delayed output signal. The module consists of an amplifier-comparator and a delay circuit.

A block diagram of the system generating a time delay is shown in Figure 2. The time delay is preset by the main microprocessor by I/O ports. Presetting can take place every  $0.1\ \text{ms}$ . The microprocessor system calculates the necessary number of system clock impulses to be counted.

The impulse frequency is stabilised by a quartz resonator at the level of  $928.834 \pm 5 \cdot 10^{-4}$  kHz (this value was measured with a frequency meter of the PFL-20 type).

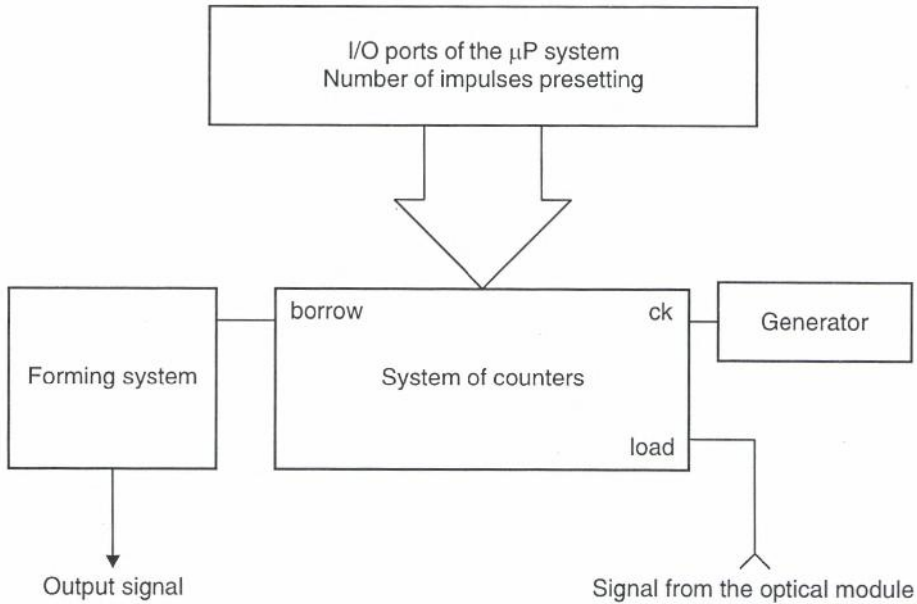


Figure 2. A block diagram of the system generating a time delay.

The quartz resonator ensures oscillation stability at the level of  $10^{-8}$ . The scale coefficient of 1.077 was used for calculations yielding the time measurement error of  $3.5 \cdot 10^{-4}$ , which—for 60 ms—gave  $20 \mu\text{s}$ . For the preset time delay of 0 ms, the system counts down one oscillation period, that is, the real delay is  $1.1 \mu\text{s}$ . The predicted time generated error should be smaller than  $30 \mu\text{s}$ . At the instant the signal from the optical system appears, the preset number is loaded to the impulse counter. The counter starts counting down the impulses from the generator.

At the instant the system reaches zero, the impulse to the forming system is generated.

This system forms an output signal, the time delay of which is equal to the time that is the product of the number of impulses and the duration of one impulse. The system returns to its initial state after the obstacle that crossed the light beam has been removed. The time courses of signals in the delay system are shown in Figure 3.

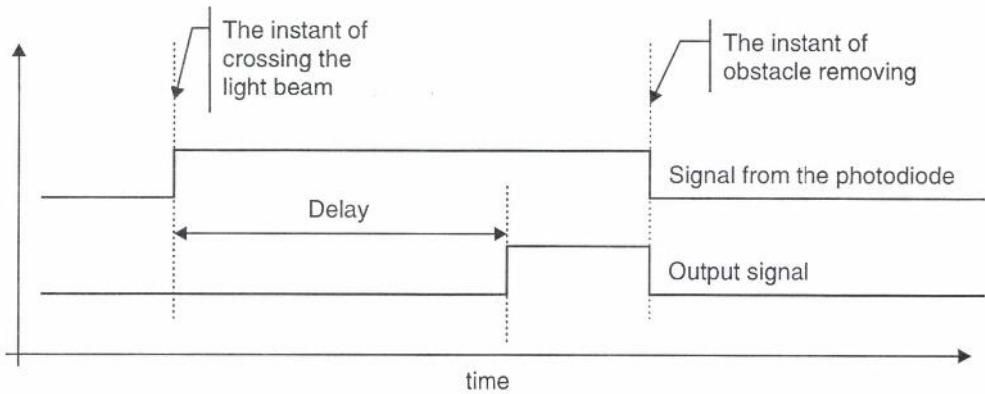


Figure 3. Time courses of signals in the delay system.

## 2.2. Accuracy of the Preset Time Delay Generated by the Calibrating Device

The basic functions realised by the calibrating device simulating an ESPD are as follows:

1. positioning the detection zone border,
2. detecting the instant the detection zone border has been crossed,
3. generating the preset time delay,
4. changing the output signal after the preset time delay has been generated.

Because the system under consideration should check and calibrate the experimental stand, the accuracy of the presetting of the time delay must also be checked. A series of tests was made by means of presetting different time delays, which were then measured using a frequency meter of the PFL-20 type. This frequency meter allows time measurement accuracy of  $\pm 10^{-6}$ , thus making its error negligible. The measurements of 30 different randomly preset time delays were taken. A random number generator of uniform distribution within the range [0,65] was used for presetting. After generation, the numbers formed an increasing sequence. Ten penetrations were made for each preset time delay. The time delay between the appearance of the signal informing that the light beam had been crossed and the generation of the output signal in the forming system was then measured with a frequency meter.

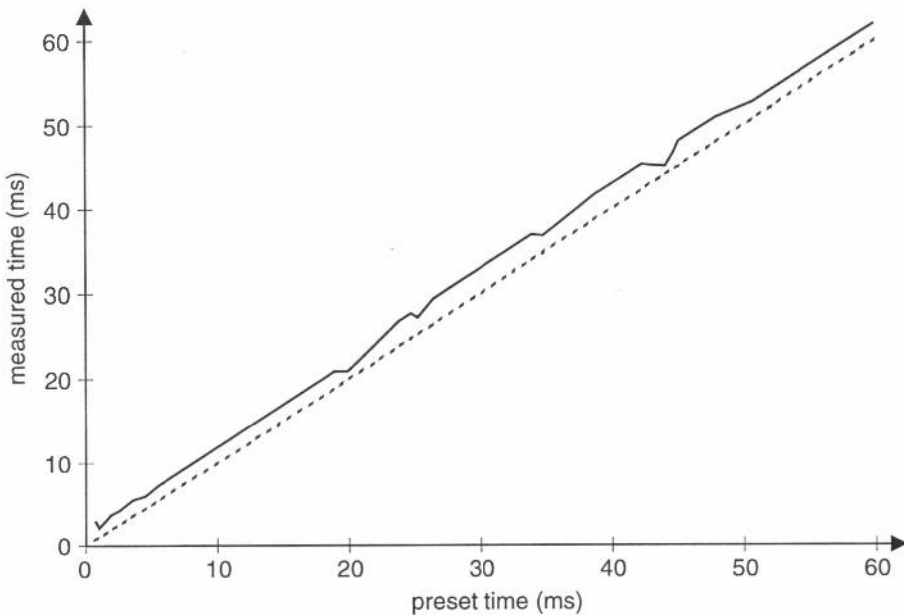


Figure 4. Experimental characteristic of the system generating the preset time delay.

The measurement error did not exceed the theoretical prediction of  $30 \mu\text{s}$ . Because of the way a calibrating device works, the error was always positive.

Taking into account the error influenced by the frequency meter, it can be said that the preset time delay generation is subject to an error smaller than  $40 \mu\text{s}$ . The system characteristic determined on the basis of measurement results is shown in Figure 4.

For the SBUO1 stand to be calibrated in a proper way, the calibrating system accuracy should be of one order of magnitude higher than that obtained by the stand.

As we want to obtain the response time measurement accuracy of at least  $\pm 1 \text{ ms}$ , the calibrating system accuracy should be of at least  $\pm 0.1 \text{ ms}$ . The results obtained have proved that the calibrating system generates a time delay standard with the accuracy high enough for checking and calibrating the SBUO1 stand.

### 3. DETERMINATION OF THE MEASUREMENT ERROR

Dźwiarek (1997) presented the relation between the response time of the device under consideration, the time measured  $t_p$ , and the penetration



speeds  $v_m$ ,  $v_d$ . The formula was derived on the assumption that the distance  $l$  measured during the second penetration (DŹwiarek, 1997) is equal to the length  $L$  determined in the first penetration.

$$l = L \quad (1)$$

However, due to measurement errors always present in a real process, this equation is not true. Taking those errors into account, we can rewrite the formula<sup>1</sup> for  $t_r$  as follows:

$$t_r = \frac{t_p}{1 - \frac{v_m}{v_d}} + \frac{l - L}{v_d - v_m} \quad (2)$$

where  $t_r$ —response time,  $t_p$ —measured time,  $v_m$ —low speed of penetration,  $v_d$ —high speed of penetration,  $l$ —distance measured during the second penetration,  $L$ —length determined in the first penetration.

Knowing  $t_p$ ,  $L$ ,  $l$ ,  $v_m$ , and  $v_d$ , we can, therefore, determine the response time.

We can find the measurement error from the formula for a total differential, which yields

$$\Delta t_r = \left| \frac{\delta t_r}{\delta t_p} \Delta t_p \right| + \left| \frac{\delta t_r}{\delta v_m} \Delta v_m \right| + \left| \frac{\delta t_r}{\delta v_d} \Delta v_d \right| + \left| \frac{\delta t_r}{\delta l} \Delta l \right| + \left| \frac{\delta t_r}{\delta L} \Delta L \right| \quad (3)$$

where

$$\frac{\delta t_r}{\delta t_p} = \frac{1}{1 - \frac{v_m}{v_d}} \quad \frac{\delta t_r}{\delta l} = \frac{1}{v_d - v_m} \quad \frac{\delta t_r}{\delta L} = \frac{-1}{v_d - v_m}$$

$$\frac{\delta t_r}{\delta v_m} = \frac{t_p}{v_d \left(1 - \frac{v_m}{v_d}\right)^2} + \frac{l - L}{(v_d - v_m)^2} \quad (4)$$

$$\frac{\delta t_r}{\delta v_d} = \frac{t_p v_m}{v_d^2 \left(1 - \frac{v_m}{v_d}\right)^2} + \frac{l - L}{(v_d - v_m)^2}$$

<sup>1</sup>  $v_d \cdot t_p + v_m \cdot t_r = v_d \cdot t_r$

$$t_r = \frac{t_p}{1 - \frac{v_m}{v_d}}$$

It is obvious that the smallest measurement errors appear when the following conditions are satisfied:

$$v_d \gg v_m \text{ and } l = L \quad (5)$$

where  $v_d$ —high speed of penetration,  $v_m$ —low speed of penetration,  $l$ —distance measured during the second penetration,  $L$ —length determined in the first penetration.

Equation 2 can be then rewritten as

$$t_r = t_p \quad (6)$$

where  $t_r$ —response time,  $t_p$ —measured time; whereas Equations 3 and 4 take the form

$$\Delta t_r = \left| \Delta t_p \right| + \left| \frac{t_p}{v_d} \Delta v_m \right| + \left| \frac{t_p v_m}{v_d^2} \Delta v_d \right| + \left| \frac{\Delta l}{v_d} \right| + \left| \frac{\Delta L}{v_d} \right| \quad (7)$$

The following conditions are fulfilled in the course of the measurement:

$$v_d > 2000 \text{ mm/s} \quad v_m \approx 1 \text{ mm/s} \quad \text{and} \quad l = L \quad t_p < 50 \text{ ms} \quad (8)$$

Under these conditions the influence of errors  $\Delta v_m$  and  $\Delta v_d$  is negligible. Finally, we have

$$\Delta t_r = \left| \Delta t_p \right| + \left| \frac{\Delta l}{v_d} \right| + \left| \frac{\Delta L}{v_d} \right| \quad (9)$$

From Equation 9 it follows that when measuring response time, it is not necessary to measure penetration speed, provided conditions in Equation 8 are satisfied. For the measurement error to be assessed, we should determine the errors  $\Delta l$ ,  $\Delta L$ ,  $\Delta t_p$  first.

#### 4. EXPERIMENTAL VERIFICATION OF THE MEASUREMENT ACCURACY

As shown in previous sections, measuring ESPD response time with the DPM is subject to the following errors: (a) localisation errors, that is,

those made in the localisation of the detection zone border; (b) rod position measurement errors made during high-speed penetration; and (c) time delay measurement errors.

The values of all those components of the total error have been determined experimentally using the equipment described in section 2.

#### 4.1. Characteristic of the Rod Position Measuring System in Low-Speed Penetration

In order to determine the rod position errors influenced by a non-linear characteristic of the converter and counting errors, the measurements were taken within the whole motion range of the actuator rod. The experiments were performed at the preset time delay of the calibrating system equal to zero. The actuator rod translation was measured starting at the instant the output relay had switched to the moment at which the light beam was crossed. The rod translation was measured by means of an electronic length meter revealing the accuracy up to  $\pm 0.02$  mm. The length meter was cleared for the light beam localisation, for which the position measurement system of the SBUO1 stand showed 30 units. The measurements were taken at the penetration speed of about 1 mm/s. Under such conditions the influence of the output relay response time was negligible, and the slips could be neglected, too. The measurements were taken every 10 mm. For each position of the light beam 10 measurements were taken and the mean value as well as the mean square deviation were calculated.

The measurement results obtained with the use of converter,  $P_i$ , and length meter,  $L_i$ , were different. This was due to constant translation  $w$  (mm), whose length depended on both the point at which the length meter was cleared and the angle-to-impulse converter scale coefficient  $k$  (mm/unit). These constants were evaluated using the least squares method (Jaworski, Morawski, & Ołędzki, 1992). In this method the following condition should be satisfied:

$$M = \sum_{i=1}^n (L_i + w - kP_i)^2 = \min \quad (10)$$

where  $n = 23$  is the number of measurement points.

The condition in Equation 10 is satisfied when

$$\frac{\delta M}{\delta k} = \sum_{i=1}^n 2 (kP_i^2 - (L_i + w)P_i) = 0 \quad (11)$$

and

$$\frac{\delta M}{\delta w} = \sum_{i=1}^n 2 (kP_i - (L_i + w)) = 0 \quad (12)$$

Equations 11 and 12 have the solution

$$w = \frac{\sum_{i=1}^n L_i - k \sum_{i=1}^n P_i}{n} \quad (13)$$

$$k = \frac{n \sum_{i=1}^n L_i P_i - \sum_{i=1}^n L_i \sum_{i=1}^n P_i}{n \sum_{i=1}^n P_i^2 - \sum_{i=1}^n P_i \sum_{i=1}^n P_i}$$

In our case

$$\sum_{i=1}^n L_i = 2530 \quad \sum_{i=1}^n P_i = 3181.04 \quad (14)$$

$$\sum_{i=1}^n L_i P_i = 449540.80 \quad \sum_{i=1}^n P_i^2 = 538034.55$$

Substituting Equation 14 into Equation 13 yields

$$k = 1.0158 \text{ mm/unit} \quad w = 30.49 \text{ mm} \quad (15)$$

where  $k$ —angle-to-impulse converter scale coefficient and  $w$ —constant translation.

The experimental results normalised in terms of the calculated values of coefficients  $k$  and  $w$  are given in Table 1. We can assume the maximal deviation  $\Delta L$  from the straight line described by Equation 16

$$L + w = kP \quad (16)$$

as the converter linearity error  $\Delta L_{lin}$ , where  $L$ —length determined in the first penetration,  $w$ —constant translation,  $k$ —angle-to-impulse converter scale coefficient,  $P$ —length determined with the use of a converter.

TABLE 1. Determination of the Converter Linearity Error

Parameters	Measurement Points											
	1	2	3	4	5	6	7	8	9	10	11	12
$L_i + w$	30.49	40.49	50.49	60.49	70.49	80.49	90.49	100.49	110.49	120.49	130.49	140.49
$kP_i$	30.47	40.42	50.58	60.44	70.51	80.39	90.49	100.51	110.43	120.47	130.53	140.50
$\Delta$	0.02	0.07	-0.09	0.05	-0.02	0.10	0.0	-0.02	0.06	0.02	-0.04	-0.01

Parameters	Measurement Points											
	13	14	15	16	17	18	19	20	21	22	23	
$L_i + w$	150.50	160.50	170.50	180.50	190.50	200.50	210.50	220.50	230.50	240.50	250.50	
$kP_i$	150.59	160.60	170.50	180.51	190.51	200.55	210.54	220.47	230.58	240.39	250.34	
$\Delta$	-0.09	-0.1	0.0	-0.01	-0.01	-0.05	-0.04	0.03	-0.08	0.11	0.16	

Notes.  $L_i$ —results of displacement measurement obtained with the use of a length meter,  $w$ —constant translation,  $k$ —angle-to-impulse converter scale coefficient,  $P_i$ —results of displacement measurement obtained with the use of an angle-to-impulse converter,  $\Delta$ —converter linearity error.

The diagram  $kP = f(L + W)$  is shown in Figure 5.

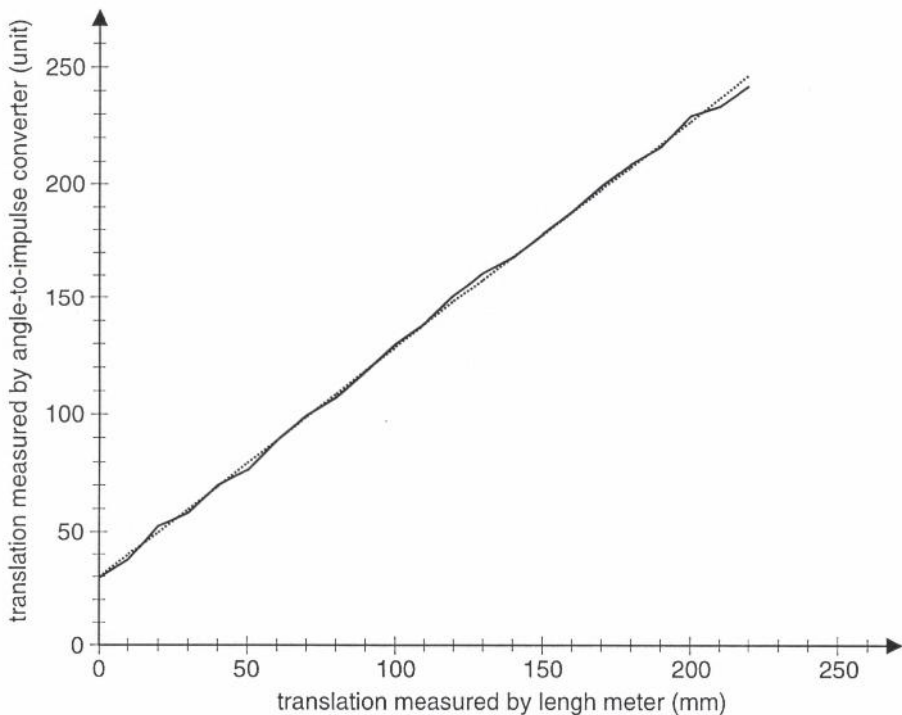


Figure 5. Characteristic of the rod position measuring system in low-speed penetration.

From Figure 5 and Table 1 it can be easily seen that maximal linearity errors appear in the extreme parts of the measurement area. The real measurements will be taken at the detection zone border located in the central part of this area, that is, within the range of 100–200 mm translations of the rod. In this range the linearity error is

$$\delta L_{lin} \leq \pm 0.1 \text{ mm} \quad (17)$$

The random error of the rod position measurement in low-speed penetration can be, therefore, written as follows:

$$\delta L_p = \delta L = \delta L_{lin} + \delta_x \leq (0.1 + 0.55) \text{ mm} = \pm 0.15 \text{ mm} \quad (18)$$

where  $\delta_x$ —experimental standard deviation.

As under real conditions response time cannot be equal to zero, the following systematic error should be added to the random error (Dźwiarek, 1997):

$$\delta L_s = t_r v_m < 50 \cdot 1 \text{ ms} \cdot \text{mm/s} = 0.05 \text{ mm} \quad (19)$$

## 4.2 Characteristic of the Rod Position Measuring System in High-Speed Penetration

The effects appearing in the mechanical parts of the rod position measuring system of the SBUO1 stand in high-speed penetration (e.g., slips and deformations), may change the characteristic of the system when compared to that for low-speed penetration. The measurements were, therefore, taken again at the maximal speed reached by the actuator. This speed varied depending on the changes in the position of the light beam, reaching its maximum near the centre and decreasing in the extreme parts of the measurement area. It resulted from the way of the actuator operation, that is, the rod accelerated at the first stage of motion and then slowed down. The rod speed, however, during measurements was always higher than 2000 mm/s. Before the measurements, it was found that the clearing point of the electronic length meter did not change its position. The checking was repeated after the measurement proving that the stand vibrations appearing at high speeds did not change the structure of the mechanical module. The results obtained at

this speed revealed the mean square deviation  $\sigma_x$  of higher value. New values of the coefficients  $k_d$  and  $w_d$  were calculated:

$$\begin{aligned}
 n = 23 \quad \sum_{i=1}^n L_i &= 2530 \quad \sum_{i=1}^n P_i = 3172.96 \\
 \sum_{i=1}^n L_i P_i &= 448601.20 \quad \sum_{i=1}^n P_i^2 = 535702.50 \quad (20) \\
 k_d &= 1.0161 \text{ mm/unit} \quad w_d = 30.17 \text{ mm}
 \end{aligned}$$

It can be seen that the change of characteristic's slope  $\Delta k$  is

$$\Delta k = k_d - k = 0.0003 \text{ mm/unit} \quad (21)$$

TABLE 2. Determination of the Linearity Error in High-Speed Penetration

Parameters	Measurement Points											
	1	2	3	4	5	6	7	8	9	10	11	12
$L_i + w$	30.17	40.17	50.17	60.17	70.17	80.17	90.17	100.17	110.17	120.17	130.17	140.17
$kP_i$	30.34	40.11	50.09	60.10	70.13	80.17	90.08	100.10	110.14	120.25	130.27	140.27
$\Delta$	-0.17	0.06	0.08	0.07	0.04	0.00	0.09	0.07	0.03	-0.08	-0.1	-0.10

Parameters	Measurement Points										
	13	14	15	16	17	18	19	20	21	22	23
$L_i + w$	150.17	160.17	170.17	180.17	190.17	200.17	210.17	220.17	230.17	240.17	250.17
$kP_i$	150.24	160.32	170.30	180.30	190.32	200.16	210.13	220.10	230.08	240.09	249.89
$\Delta$	-0.07	-0.15	-0.13	-0.13	-0.15	0.01	0.04	0.07	0.09	0.08	0.28

Notes.  $L_i$ —results of displacement measurement obtained with the use of a length meter,  $w$ —constant translation,  $k$ —angle-to-impulse converter scale coefficient,  $P_i$ —results of displacement measurement obtained with the use of an angle-to-impulse converter,  $\Delta$ —converter linearity error.

The measurement error due to this effect is

$$\Delta l_k = \Delta k \cdot P < 0.06 \text{ mm} \quad (22)$$

More crucial, however, is the change in position of the characteristic's zero point:

$$\Delta w = w - w_d = 0.32 \text{ mm} \quad (23)$$

The normalised measurement results are given in Table 2.

It is, therefore, obvious that in the range of 100–200 mm we can assume

$$\delta l_{lin} \leq \pm 0.15 \text{ mm} \quad (24)$$

where  $\delta l_{lin}$ —linearity error defined as the maximal deviation from the straight line.

Finally, the systematic error made in the length  $l$  measurement can be rewritten as follows:

$$\Delta l_s = \Delta w + \Delta l_k < 0.38 \text{ mm} \quad (25)$$

and the random error as

$$\delta l_p = \delta l_{lin} + \sigma_x \leq \pm 0.23 \text{ mm} \quad (26)$$

Figure 6 shows the characteristic of the system in high-speed penetration.

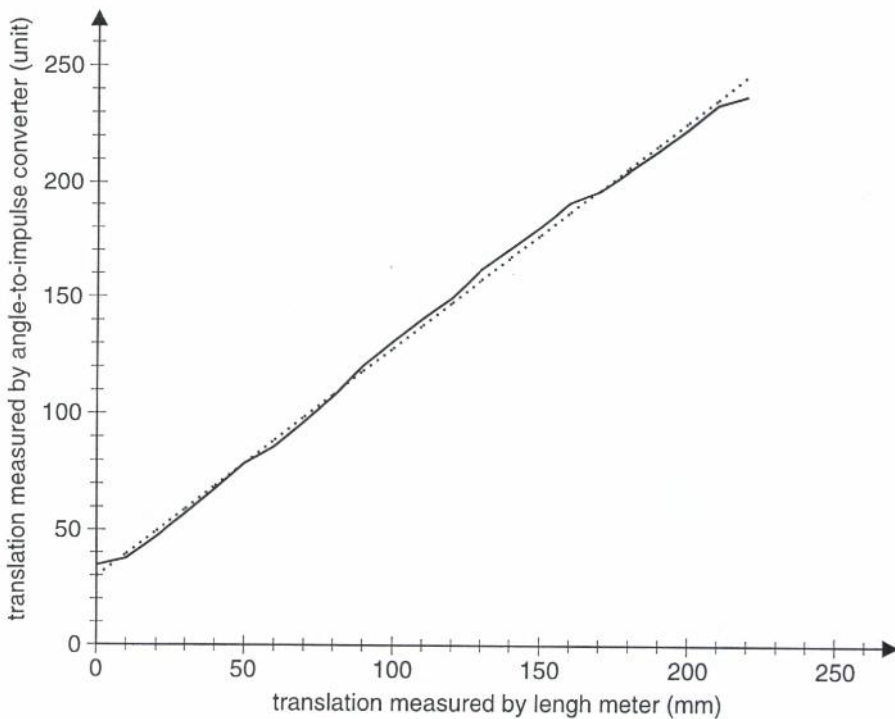


Figure 6. Characteristic of the rod position measuring system in high-speed penetration.



### 4.3. Time Measurement Accuracy Obtained on the SBUO1 Stand

When determining the characteristic of the time measuring system, it is crucial to be independent of the position measurement. It is then possible to omit the influence of the  $\Delta l$  and  $\Delta L$  errors upon its determination accuracy. We have reached that by using internal signals of the microprocessor system. The internal signal of the control system—instead of the signal coming from the optical module—informing about the start of the time measurement was transmitted to the system generating a time delay in the calibrating system. The time delay generation in the calibrating system started, therefore, at the instant the control system started the time measurement instead of the moment at which the light beam crossing was detected. As a result, the position measurement errors exerted no influence upon the time measurement results.

Time is measured on the SBUO1 stand at the step of 1 ms. The characteristic of time measurement system is then step-wise. To determine it, measurements were taken at both ends of each step. To avoid random errors, each value was measured 10 times.

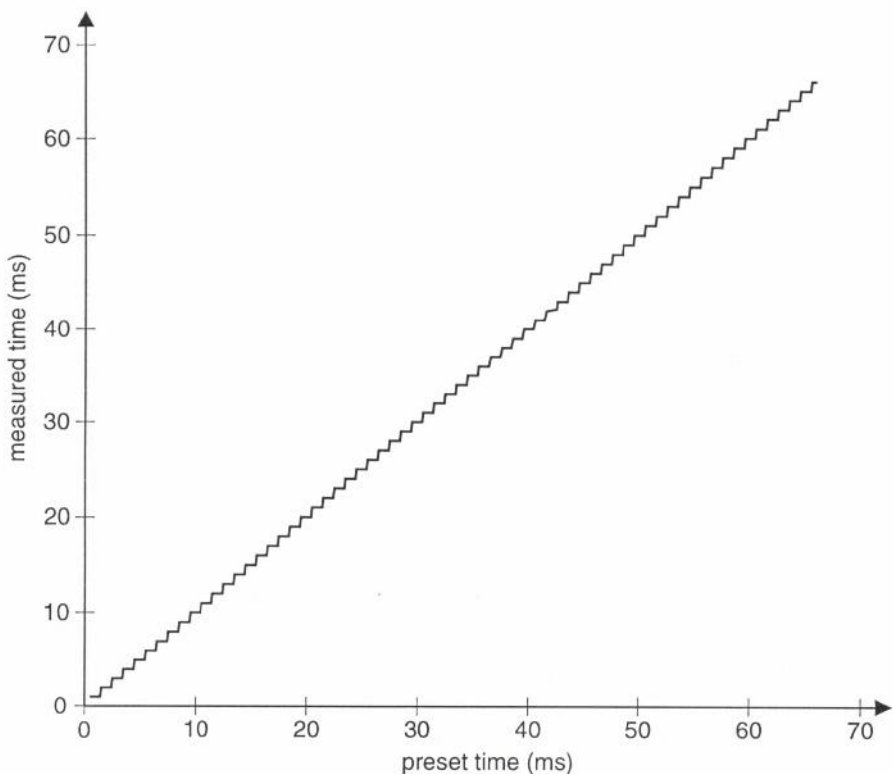


Figure 7. Characteristic of the time measuring system.

There was practically no scatter of measurement results within the range of 0–34 ms and the steps of the characteristic corresponding to the time  $t$  were inside the interval  $[t + 0.4, t + 0.5]$ . The scatter appeared within the range of 35–41 ms, which meant that within this range the steps of the characteristic were in the neighbourhood of the point  $t + 0.5$  ms. For the 42 ms measurements, the scatter of results disappeared again and the steps were in the interval  $[t + 0.5, t + 0.6]$ . Within the whole range of measurement, the step was shifted by 0.1 ms due to calculation errors appearing when counting the time of 1 ms in the control system.

The characteristic of the time measurement system is shown in Figure 7.

Figure 8 shows the characteristic of the time measurement error  $\Delta t_z$ , defined as the difference between the measured,  $t_p$ , and the preset,  $t_{us}$ , time delays:

$$\Delta t_z = t_p - t_{us} \quad (27)$$

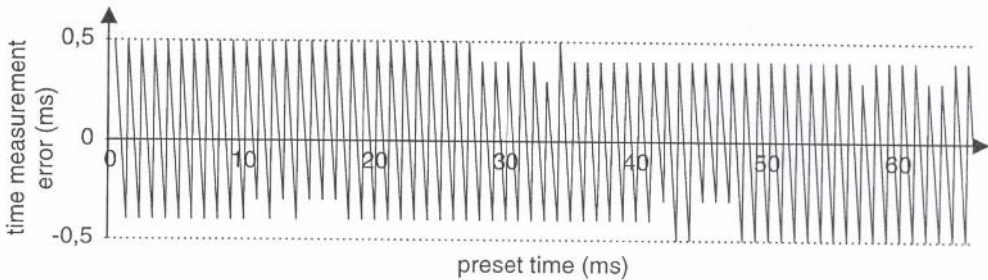


Figure 8. Characteristic of the time measurement error.

It should be emphasised that within the whole range of measurement, the  $\Delta t_z$  error is smaller than 0.5 ms. As the characteristic shown in Figure 8 was determined with the accuracy of  $\pm 0.05$  ms, the error in the measurement of the time delay on the SBUO1 stand is

$$\delta t_z = \pm 0.55 \text{ ms} \quad (28)$$

#### 4.4. Total Measurement Error

The experiments just described made it possible to determine all the components of the measurement error in Equation 9. As the speed  $v_d$  is

always higher than 2000 mm/s, we have the following formula for the systematic error:

$$\Delta t_s < (\Delta L_s + \Delta I_s) / 2000 \text{ mm/s} = 0.43 / 2000 \text{ s} < 0.22 \text{ ms} \quad (29)$$

As random errors add geometrically, we have

$$\Delta t_p < \sqrt{\frac{0.15^2 + 0.23^2}{2000^2} + 0.55^2} = 0.57 \text{ ms} \quad (30)$$

And, finally,

$$-0.79 \text{ ms} \leq \Delta t_r \leq 0.35 \text{ ms} \quad (31)$$

The interval of the response time measurement accuracy (Equation 31) was obtained assuming the worst possible measurement conditions. The results obtained differ slightly from those given by Dźwiarek (1997). This is so because the effect of the shift in the position measurement characteristic in high-speed penetration was neglected before.

#### 4.5. Experimental Verification of the Total Error

The obtained results allowed to determine and assess each component of the response time measurement error. When dealing with this problem, it is very interesting to prove that the total measurement error is really enclosed within the limits assumed. Hence, a series of measurements was taken under conditions as close to real ones as possible.

Device accuracy is usually verified by several series of measurements taken for different values of a measured quantity. In this case, however, this approach would have been useless: Errors smaller than 1 ms cannot be detected because of the resolution of the display. Therefore, for a given preset response time, the measurement result remains unchanged, or takes one of the two subsequent values. For example, if the preset response time is 25.7 ms, the measurement result will be 25 or 26 ms giving a measurement error of  $-0.8$  or  $0.3$  ms irrespective of the number of measurements. The results obtained in such a way cannot provide information about the measurement accuracy within the whole range of measurements. Thus, a different approach was taken: Measurements were taken for different preset response times. For each measure-

ment, the preset response time was determined randomly (using a random-number generator of uniform distribution) taking the values from the interval 0–65 ms. As the light beam position measurement plays a very important role in the whole measurement process, the experiments were performed for four different positions of the light beam. The measurement area ranged from 0 to 250 units. From the analysis carried out, it followed that the measurements taken at the extremes of this area were subject to the largest errors. Therefore, light beam positions of 50, 100, 150, and 200.1 units were used. At each position, following the measurement procedure, calibration was performed (in low-speed penetration). Measurements were also taken. Calibration was performed for 10 different, randomly chosen response times, which enabled the calibration accuracy to be verified. A series of 30 measurements was then taken in high-speed penetration.

TABLE 3. Rates of Particular Values of the Measurement Errors ( $n$ )

$L$	$\Delta t$ (ms)												$\Delta t_{ave}$	$\sigma(\Delta t)$
	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3		
50	1	2	2	1	6	1	4	3	5	2	3	0	-0.23	0.28
100	1	2	2	2	0	2	4	3	4	4	4	2	-0.14	0.31
150	1	3	4	1	7	0	5	0	1	5	2	1	-0.28	0.32
200	0	2	6	2	4	1	3	5	2	2	2	1	-0.27	0.29
Global	3	9	14	6	17	4	15	11	12	13	12	4	-0.23	0.31

Notes.  $L$ —length determined in the first penetration,  $\Delta t$ —measurement error,  $\Delta t_{ave}$ —average value of error,  $\sigma$ —standard deviation.

To determine measurement accuracy at a particular light beam position, let us consider mean values and the scatter of errors. Table 3 presents rates  $n$  of particular values of error  $\Delta t$  for successive measurement series for all 120 measurements. It also presents mean values and mean square deviations of the errors. The differences between those two values are very small, as can be seen in the table.

On the basis of Table 3, the estimation of the cumulative distribution function of the error can be defined for each  $L$ . The event frequency is the most effective estimator (Rumszyski, 1973):

$$P(\Delta t < x_i) = k_i/n \quad (32)$$

where  $k_i$ —the number of “an error smaller than  $x_i$  occurred” events (in our case the sum of numbers left of the  $x_i$  column),  $n$ —the number of measurements taken (in our case  $n = 120$ ).

The cumulative distribution function estimated in this way approximates the real one. Taking the confidence level of .95, it is possible to establish (Firkowicz, 1970) the limits, between which lies the real cumulative distribution function:

$$\left. \begin{aligned} F_d(x_i) &= \frac{1}{1 + \frac{n+1-k_i}{k_i} f_{2(n+1-k_i), 2k_i, 0.95}} \\ F_g(x_i) &= \frac{f_{2k_i, 2(n+1-k_i), 0.95}}{\frac{n+1-k_i}{k_i} + f_{2k_i, 2(n+1-k_i), 0.95}} \end{aligned} \right\} \quad (33)$$

where  $f_{k_1, k_2, \beta}$  stands for the  $\beta$  order quantile of the Snedecor statistics for the pair of  $(k_1, k_2)$  degrees of freedom. Thus, we can determine maximal probability that the  $\Delta t$  error is smaller than  $-0.8$  and maximal probability that it is larger than  $0.3$ . The probabilities obtained for all measurement series differed insignificantly. Therefore, we have

$$\begin{aligned} P(\Delta t < -0.8) &< F_g(x_1) = 0.09 \\ P(\Delta t > 0.3) &< 1 - F_d(x_{30}) = 0.09 \end{aligned} \quad (34)$$

The results in Equation 34 prove that the real values of the measurement error lie within the interval given in Equation 30. Thus, it can be seen that the measurement accuracy remains unchanged within the specified limits for the detection zone border position changes within the interval 50–200 units.

## 5. CONCLUSIONS

The Double Penetration Method (DPM) is a unique way to measure Electrosensitive Protective Device (ESPD) response time. It has been worked out by the author in the Central Institute for Labour Protection to satisfy the needs of the certification of those devices. This method can also be used to examine various protective device prototypes in the course of the design process.

The use of the DPM allows to overcome many obstacles appearing in the course of the measurement of ESPD response time; for example, the laborious and time consuming measurement process, limited possibilities of measurement process automatization, serious difficulties appearing when measuring under environmental stress conditions, and so forth. One can, therefore, limit the factors affecting the uncertainty of the measurement.

The DPM was used on the measurement stand SBUO1 supplied with a computer control system. Repeatability and reproducibility of the measurement results increased considerably and the cost of the measurements was reduced. The stand design allows measurements on a shaker, in a climatic or electromagnetic compatibility chamber.

Three different ways were used to validate the method:

- theoretical analysis of the measurement accuracy,
- calibration of the stand using the traceability method that enables one to compare the obtained results with international standards,
- a series of measurements of a known response time and determination of the obtained accuracy.

The measurement schedule allowed to check the measurement accuracy as well as repeatability and reproducibility. Both theoretical and experimental results were in excellent agreement and satisfied the requirements of International Organization for Standardization and International Electrotechnical Commission (1997) and Polski Komitet Normalizacyjny (1995). The measurement results prove that the total response time measurement error lies within  $[-0.8 \text{ ms}, 0.4 \text{ ms}]$  in the entire measuring range. Thus, it has been proved that the Double Penetration Method makes it possible to obtain measurement results of ESPD response time, whose accuracy, repeatability, and reproducibility, are satisfactory enough to be assessed objectively.

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