A Method for Response Time Measurement of Electrosensitive Protective Devices

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A great step toward the improvement of safety at work was made when electrosensitive protective devices (ESPDs) were applied to the protection of press and robot-assisted manufacturing system operators. The way the device is mounted is crucial. The parameters of ESPD mounting that ensure safe distance from the controlled dangerous zone are response time, sensitivity, and the dimensions of the detection zone. The proposed experimental procedure of response time measurement is realized in two steps, with a test piece penetrating the detection zone twice. In the first step, low-speed penetration (at a speed \( v_m \)) enables the detection zone border to be localized. In the second step of measurement, the probe is injected at a high speed \( v_d \). The actuator rod position is measured and when it is equal to the value \( L \) registered by the earlier measurements, counting time begins as well as the monitoring of the state of the equipment under test (EUT) output relays. After the state changes, time \( t_p \) is registered. The experimental procedure is realized on a special experimental stand. Because the stand has been constructed for certification purposes, the design satisfies the requirements imposed by Polski Komitet Normalizacyjny (PKN, 1995). The experimental results prove the measurement error to be smaller than \( \pm 0.6 \) ms.

1. INTRODUCTION

Great progress observed nowadays both in science and technology stimulates designers to invent new, increasingly effective machines that improve production efficiency. They permit constant growth of production but their application introduces new hazards for operators and all persons in the vicinity of the dangerous parts of machinery. A great step toward the improvement of safety at work was made when electrosensitive protective devices (ESPDs) were applied to the protection of press and robot-assisted manufacturing system operators. Changes in the optical, electrostatic, electromagnetic, and so forth, fields—when the presence of either a part of the human body or a thing is sensed—are applied in ESPDs to prevent a machine from starting work, or to stop its dangerous motions. These are, for example, electrooptical protective devices (light curtains, photoelectric relays), ultrasonic protective devices, capacitive, or inductive protective devices.

Noncontact limit switches (e.g., proximity detectors) are not classified as ESPDs. Widespread application imposes on ESPDs strong requirements related especially to their reliability and adaptability to the working environment. For the safety functions to be realized properly, ESPDs should be sufficiently immune to all disturbances taking place during operation. The way the device is mounted is also crucial. The parameters of ESPD mounting that ensure safe distance from the controlled dangerous zone are response time, sensitivity, and the dimensions of the detection zone (Bell & Frederickson, 1994; Comité Européen de Normalisation, 1995).

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Experimental methods have been developed and special experimental stands have been built for certification purposes at the Central Institute for Labour Protection, in Warsaw, Poland. Whereas straightforward methods exist for measuring sensitivity and the dimensions of the detection zone, satisfactory methods have not been developed yet for measuring the response time. The response time is defined as the time between the occurrence of the event leading to the actuation of the sensing function and the output signal switching devices (OSSDs) achieving the off-state (International Electrotechnical Commission [IEC], in preparation). The most popular method used nowadays to measure the ESPD response time consists in an electronic simulation of the detection zone disturbance. The simulation process is realized by generating corresponding electric signals in an internal electronic system of the device tested. The measurement result suffers from an error due to both neglecting the response times of the detection zone elements and the delay influenced by the detection zone scanning time. When using this method, the simulation procedure should be formulated for each operational principle of the tested device separately. Another disadvantage of this method is that there has to be access to the internal systems of the device, which can raise doubts about the method's impartiality, especially in controversial cases.

Another method consists in injecting a test piece into the detection zone at the speed of 2 m/s. The instant the detection zone is penetrated is registered by a high-speed camera (Dei-Svaldi, Kneppert, & Vautrin, 1995; Grigulewitsch & Reinert, 1989). The detection zone border is localized with a test piece that penetrates the detection zone to actuate the sensing function. The probe is then pulled back. The detection zone border is assumed at the point where a 1-mm translation of the probe causes a change of the output signal. Applying this measurement procedure is extremely difficult and its automatization is almost impossible.

I propose a new method for measuring the response time. In this method, the detection zone is penetrated twice, at different speeds (Dźwiarek, 1996). The experimental procedure is realized on a special experimental stand (Figure 1). As the stand has been constructed for certification purposes, the design satisfies the requirements imposed by PKN (1995). The accuracy, repeatability, and reproducibility of results are of special importance.

2. METHOD

The experimental procedure of response time measurement takes place in two steps; that is, a test piece penetrates the detection zone twice. In the first step, low-speed penetration (at a speed $v_m$) enables the detection zone border to be localized (Figure 2). The signal of the start of the measurement activates the measurement of the probe position. At the same time, the equipment under test (EUT) output relays contacts are monitored. After the response time $t_r$ from the moment the detection zone border is crossed, these elements switch. At this moment, the number on the actuator rod position counter, representing the distance that the probe has traveled since the beginning of measurement is registered. We can then write

$$L = L_0 + dL$$

$$dL = v_m \cdot t_r$$

(1)

where $dL$ is the penetration depth of the test piece before the relays switch. Distance $L$ is registered and will be applied to the detection of the zone border localization in the next measurement step.

In the second step of the measurement, the probe is injected at a high speed $v_d$. The actuator rod position is measured in the same way as in the previous step. When the position becomes equal to the value $L$ registered by the earlier measurements, counting time begins as well as
Figure 1. Experimental stand for certification testing of the ESPDs.

Figure 2. Penetration at a speed $v_{rr}$. 
the monitoring of the state of the EUT output relays. After the state changes, time $t_p$ is registered (Figure 3). We have

$$dl + dL = v_d * t_r$$

As Equation 1 is valid and taking into consideration that

$$dl = v_d * t_p$$

we finally obtain

$$v_d * t_p + v_m * t_r = v_d * t_r$$

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

Therefore, on the basis of the measured value $t_p$ and the known values of speed $v_d$ and $v_m$, we can determine the response time. Measuring time $t_p$ as well as both displacements $L$ and $dL$ with sufficient accuracy is not difficult in practice. The problem of speed measurement is rather complicated, though. The measurement accuracy is also affected by the fact that two different response times may appear in the two steps of the measurement mentioned before. Both of these problems can be solved if the condition

$$v_m \leq v_d$$

is satisfied.

So

$$v_m * t_r = 0$$

which leads to the transformation of Equation 4 into

$$t_r = t_p$$

From these equations it follows that if Equation 5 is true, it is possible to make the measurement independent of speed.
3. EXPERIMENTAL STAND

The experimental procedure described in the previous section is carried out on the experimental stand SBUO1 (Dźwiarek, 1996; Dźwiarek & Kowalewski, 1994, 1995). The penetrating actuator is a 523 120 0640 type, 320 mm long. The quick-release valve (type 573 504 0100) that controls the air outflow from the actuator enables the speed to range from 0.1 to 2500 mm/s. All pneumatic elements were manufactured by Mannesman Rexrot (Germany). Figure 4 shows the equipment for the response time measurement.

The actuator rod position is measured using an angle-to-impulse converter of the E21MPL10S type manufactured by PZO (Poland). The rod translation is converted into revolution of the roll, 16 mm in diameter. The converter generates 500 impulses per revolution counted by an electronic system. The rod diameter has been selected in a way ensuring correspondence between one impulse and the rod translation of 0.1 mm.

The signal of the start of the measurement is generated by a limit switch (type 894 041 200 2). Its position on the actuator ensures the smallest possible influence of the slips on measurement accuracy.

Time is measured by a generator synchronized by a 12-MHz quartz resonator. A resonator of this type ensures the short-time frequency change to be of the $10^{-10}$ order. The timing period is 1 ms. A microprocessor controls the counting.

The speed of the actuator rod is measured in terms of measuring its translation in a predetermined time. In the first step of the measurement, that is, when the detection zone border is being localized, the measurement takes 1 s, enabling speeds within the range of 0.1 to 100 mm/s to be measured. The speed measurement time in the second step of the measurement is 20 ms, increasing the possibility that speeds higher than 5 mm/s can be measured. The speeds we measure, however, are higher than 100 mm/s and, therefore, poor accuracy of measurement for speeds lower than 100 mm/s can be overlooked.

A computer controls the measurement process enabling its automatization and increasing test impartiality.

Figure 4. Equipment for the response time measurement.
4. ANALYSIS OF MEASUREMENT ERRORS

Because the response time measurement consists of two steps, errors appearing in both of them affect the results. The analysis of errors will, therefore, be also divided into two parts corresponding to the measurement procedure (Dzwiarek, 1996).

4.1. Localization of the Detection Zone Border

Localization of the detection zone border is subject to errors from several sources, particular contributions of which are difficult to separate. Therefore, an analysis of errors from all the sources is carried out further in this article.

A diagram of the procedure for the localization of the detection zone is shown in Figure 2. A more detailed description of the phenomena appearing in the course of the measurement is shown in Figure 5. It should be noted, however, that only the qualitative representation of the measurement process is given. The real proportions between particular periods of time are, of course, different.

From Figure 5 it follows that four characteristic stages can be distinguished in the course of the measurement. In the first stage, the actuator accelerates. The measurement is taken slowly. Therefore, it can be assumed that the speed becomes steady before the actuator reaches the limit switch. So, at the next stages it remains constant and equal to \( v_m \). At this time the device is waiting for the limit switch actuation when the reset signal for the position counter is generated.

Stage II begins with the rod position at which the limit switch actuates. From this instant until the moment when the signal from the switch is received is its response time \( t_w \). The distance \( dL_1 \) traveled by the actuator in this time can be written as

\[
dL_1 = v_m \cdot t_w
\]  

(8)

On the basis of the measurement results, it has been determined that \( t_w < 0.5 \text{ ms} \) (Dzwiarek, 1996).

At Stage III, the actuator position is measured with an angle-to-impulse converter. The impulse distribution uniformity error of less than 0.5% is guaranteed by the manufacturer. The errors may also come from other sources, for example, imperfections in the manufacturing of the roll, eccentricity of its mounting, and counting. The measurements performed have proved
that the errors ($\Delta L$) due to the transducer nonuniformity, roll manufacturing imperfections, and possible slips were negligible. We can, therefore, write

$$\Delta L = \pm 0.05 \text{ mm}$$  

Stage IV takes time $t_r$, which is the tested device’s response time until the penetration of the detection zone. This time is usually shorter than 100 ms. The actuator travels the distance of $dL_2$ in this time, the length of which is proportional to the injection speed

$$dL_2 = t_r \cdot v_m$$  

Finally, we have

$$L = L_0 - dL_1 + dL_2 \pm \Delta L$$

4.2. Response Time Measurement

The phenomena accompanying the detection zone injection at a high speed $v_d$ also constitute a source of measurement errors. These phenomena are shown in Figure 6. As in the previous step, one can also distinguish here four measurement stages. The first stage, at which the actuator accelerates, is an auxiliary one and does not contribute to the measurement process. Elements crucial for the measurement process appear in the next stages, after the limit switch actuation. Like in the previous step, the switching time errors also affect the measurement result, introducing the delay in the distance from the zone border measuring. The detection zone localization is, therefore, disturbed.

Sometimes, for high injection speeds, the actuator speed may not have enough time to stabilize. Assuming its mean speed $v_p$, we obtain

$$dl_1 = t_w \cdot v_p$$  

The detection zone border is, therefore, localized at the distance

$$l = L + dl_1 \pm \Delta L$$

We can write

$$t_p = t_r - \frac{(L - L_0 + dl_1 \pm \Delta L)}{v_d} \pm \Delta t_p$$

and, considering Equations 8, 10, 11, and 12, we have

$$t_p = t_r - \frac{(v_m \cdot t_r - v_m \cdot t_w + t_w \cdot v_p \pm 2 \cdot \Delta L)}{v_d} \pm \Delta t$$

where $\Delta t_p$ is time scale error ($\pm 0.5$ ms).

The total measurement error can be written as a sum of the following components:

- **Systematic error**

  $$\Delta t_s = t_r \cdot \frac{v_m}{v_d} - t_w \cdot (v_p - v_m)$$

- **Random error**

  $$\Delta t_r = 2 \cdot \frac{|\Delta L|}{v_d} + |\Delta t_p|$$
Because the following conditions are fulfilled (Dźwiarek, 1996)

\[ t_r < 50 \text{ ms}, \quad t_w < 0.5 \text{ ms}, \quad v_m < 1 \text{ mm/s}, \]
\[ v_d > 2,000 \text{ mm/s}, \quad v_p < 250 \text{ mm/s} \]  
(18)

we have

\[ \Delta t_s < 50 * 0.5 * 10^{-3} \text{ ms} - 0.5 * 0.125 \text{ ms} \approx 0.03 \text{ ms} \]
\[ \Delta t_r = 0.05 \text{ ms} + 0.5 \text{ ms} = 0.55 \text{ ms} \]  
(19)

and, finally, we can write

\[ \Delta t = \Delta t_r + \Delta t_s < \pm 0.6 \text{ ms} \]  
(20)

According to draft IEC 1496-1 the accuracy of ± 1 ms is required in response time measurement. The proposed method and the experimental stand can, therefore, be used in the measurement of the ESPD response time for certification purposes.

REFERENCES


