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RESEARCH ON HYSTERESIS OF TRIGGERING PROBES APPLIED IN COORDINATE MEASURING MACHINES

The article presents selected results of investigation of triggering probe hysteresis in coordinate measuring machines. The research covered the hysteresis of pretravel of one-stage triggering probes equipped with a switching transducer (represented by TP6 probe), and two-stage probes equipped with a piezoelectric transducer (e.g. TP200 probe). The effects of stylus length, measurement pressure and approach speed to the measured surface have been included in the performed tests. The variance analysis methods have been used to evaluate the effects. The results, obtained in various conditions and using different probes, have been compared. As a result, optimum values of tested parameters have been estimated, as far as they concern the operation accuracy of the probe.

Keywords: coordinate measuring machine (CMM), triggering probe

1. INTRODUCTION

Coordinate measuring machines are now the most modern measuring devices used in geometrical metrology. They enable to determine values of dimensions of the most complex machine elements with relatively high accuracy and in a time adapted to the manufacturing pace. This is extremely important in case of highly automated automobile industry. Most of the machines used there are equipped with switching probes that generate a binary signal at the contact with the measured surface. The probe is one of the most essential elements of a coordinate measuring machine. Knowledge of its operation accuracy is crucial [1-12].

The manufacturers give mostly only two parameters which define the probe's accuracy: *the pretravel variation* V_{2D}, being the difference between the maximum and minimum value of average pretravel for different measurement directions [8], and *the uni-directional repeatability max (2s)* - defined as the maximum value of double standard deviation for one measurement direction [8]. The pretravel is the distance between the point of actual contact with the measured object's surface and the point of signal triggering. In other parameters that can be found either in standards, for example [5-7], or now in catalogs of leading probe manufacturing companies, the systematic and random errors are not separated; they are considered as a total error of the measuring head. Following the PN-EN ISO 10360-2:2002 standard [5], *the measuring head error P* is the distance of radii of spherical material dimensions master, in case the measurements are performed on a measuring machine on a test sphere, using the point sampling mode and one measurement rod. The VDI/VDE standard [6] discriminates the following inaccuracies: one-dimensional V_1, two-dimensional V_2 and three-dimensional V_3 (following its guidelines) which are determined basing on location deviations, obtained as the difference of single measuring points, respectively from: a one-dimensional master (e.g. size blocks), a two-dimensional one (a ring), and a three-dimensional one (a sphere). An attempt of separating the systematic errors and the random ones of probe errors is the function *FBG* of head (tip) errors as proposed by Sładek

[4]. The FBG is a discrete function which shows the error type in the tip operation plane. The *FBG* function is being determined basing first on ring master measurements performed on the coordinate machine (similarly as V_2 in accordance with VDI/VDE), and further it is subject to harmonic analysis. Then the so-called characteristic part of the probe error function *CCFBG* which describes the systematic probe errors, and a remainder random type function *FrFBG*, are being separated.

However, the probe hysteresis and its contribution to the total inaccuracy of probe operation used in coordinate machines remains unknown. The only mention on hysteresis during operation of a triggering probe appears only once in Ratajczyk's work [3] and it is an instability of the rest point, being a measure of measuring probe tip position instability in relation to the probe axis, in non-contact (free) conditions. Anyway, this parameter has not been comprehensively investigated. It has to be pointed out that the major part of probe accuracy characteristics is being given for one operation plane only. This situation is probably due to limited possibilities of existing measurement methods of contact measuring probes, used on coordinate machines. A test set-up built in the Metrology and Measurement Systems Institute allows to extend considerably the so far existing possibilities of contact probe accuracy testing. This device enables to measure three-dimensional characteristics of pretravel in relation to any arbitrary measurement direction. Testing of probe operation hysteresis is possible as well.

2. THE HYSTERESIS OF TOUCH TRIGGERING PROBES

A split into one-stage and two-stage triggering probes [3] is used, because of distinct differences in the construction and operating principles of their transducers; however the names do not reflect fully the differences of transducer's operation.

It is possible to state, when highlighting the essential difference between the groups of above mentioned contact triggering probes, that the one-stage probe has a single transducer and its operation is related to supporting points position of the probe deflecting element. In most of the cases it is an electric contact type transducer, and its supporting points at the same time form the micro switches, connected in series [3].

The two-stage probes have additionally a second transducer, mostly of the piezo-ceramic type; its operation is independent from supporting points and is not related to them. This transducer generates the measurement signal proper, whereas the second electric contact transducer gives only a signal stating that the signal from the piezo transducer is caused by the contact of the probe tip with the measured object [3].

The hysteresis of triggering probe operation is an effect of a changed direction of measurement pressure. In case of one-stage probes, the mechanical electric contact type transducer may evidence an imperfection of structure related to misfit of seats and arms of movable elements; motion resistance caused by friction, deflection and wear of contact elements may appear as well. The above-mentioned factors are the cause of occurrence of hysteresis; the factors depend on measurement pressure, the type (weight) of the measuring tip and on switching speed.

The operation of two-stage transducers used in two-stage probes depends on the elastic deflection effect. Therefore, no motion resistance, caused by friction, appears here; this resistance is a major cause of hysteresis in probes having a single electric contact transducer. However, in the case that the two-stage probe uses an electric transducer, a hysteresis effect may be evidenced there.

In the case of both types of probes, the stability of the rest point and the point of probe tip switching have an essential effect on the stability of pretravel (therefore they affect directly the precision of probe measurement point location). In case the equilibrium conditions of transducer contact system are disturbed by a force acting on the measuring rod in another direction, e.g. when measuring a point on the opposite side of the measured element, the rest point and the point of probe tip switching may alter their positions. When switching a probe when triggered by forces acting from various directions, the following are a measure of rest point instability, point of probe tip switching instability, switching point instability, and related pretravel [10]:

- hysteresis of switching point H_P,
- hysteresis of rest point H_S,
- hysteresis of pretravel H.

At the present, no form of hysteresis as mentioned above is a parameter considered by probe manufacturers, covered by product catalog data and certificates. The manufacturers evidence only the parameters which are related to average pretravel V_{2D} and max (2s); in the most recent probe catalogs, parameters recommended by standards [5] are included, but still hysteresis is not considered there. For that reason, the users of coordinate measuring machines, equipped with triggering probes, are not aware of the hysteresis effect occurring during measurement. Therefore they do not recognize this error source when planning the measurement strategy of an element.

3. MEASUREMENT SET-UP, TESTING METHOD AND TESTED PROBES

A new computerized and fully automated measurement set-up has been developed at the Metrology and Measurement Systems Institute of Warsaw University of Technology. This set-up enables to determine all the parameters and all precision characteristics of triggering probes used in coordinate measuring machines. This method allows not only to measure the data as given by probe manufacturers, i.e. pretravel variation and repeatability in XY plane, perpendicular to the probe axis, but the actual value of probe pretravel as well. A measurement of so far unknown hysteresis types, including hysteresis of the triggering point, hysteresis of the rest point and hysteresis of pretravel is possible. All the above mentioned parameters can be measured either in XYZ space (so far, such characteristics were unknown), or in selected cross-sections [11]. Fig. 1 presents a scheme and a view of the measuring set-up.

In this concept, a moment of contact of the measuring tip with a measured object which triggers the probe action is detected. The pretravel is being measured in accordance with the definition, i.e. as a displacement of the probe tip between the contact point with the measured element and the signal triggering point. A three-dimensional distribution of the measurement points, in which probe triggering occurs when actuated from various directions in space, provides information about the inaccuracy of probe operation. This concept could supply most of the information about probe operation, but carrying it out requires a precise definition of the actual contact point (with a repeatability level of a hundredth of a micron) and needs the determination of the actual contact point, being independent from the direction of movement. This can be done by using a low pressure displacement transducer.

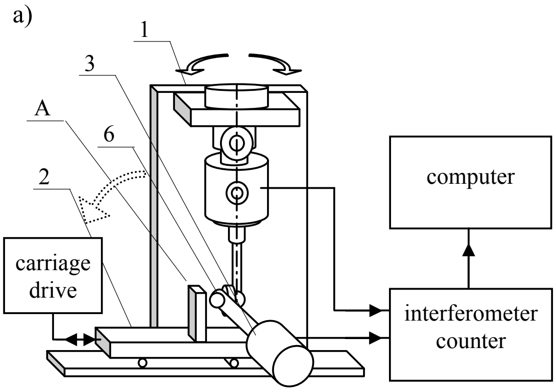
A low pressure displacement transducer being in constant contact with the probe tip is in position to detect, at high resolution, the point of tip movement and to measure its pretravel. The transducer tip is in contact with the probe tip before measurement. In order to avoid triggering the probe at such contact, the order of magnitude of such contact pressure must be at least of one level lower than that of the probe pressure. Initially the position of the transducer measuring rod, in rest position with the probe tip contact, is being registered. After mechanical triggering of the probe (by an external forcing system) at the moment of output triggering, the status of the transducer is being registered. A variation of transducer indications is a measure of pretravel. An additional difficulty of maintaining high mechanical stability of the switching system appears, because a high measurement definition at the level of 10-20 nm is required.

The high-resolution interference displacement transducer, with a low measurement pressure, is the fundamental element of the probe characteristics testing set-up. During tests, a sensor with a deflecting arm as described in articles [13,14] has been used. Due to the arm length, its operating range was 4 mm, at a resolution of approx. 0,015 μm.

The measuring pressure was at the level of 5 mN approximately and its variation did not exceed a few percent, within the whole measuring range. As the measuring pressure of the displacement transducer is some tens lower than the tested probe switching pressure (100 mN minimum approximately.), it can be assumed that the interaction between the measuring head tip and the tested probe tip can be negligible.

The system which actuates the displacement of the tested probe tip consists of a carriage with bearings and of drive elements. Flat surfaces *4* of the carriage *2* do not act directly on the tip *5* of the tested probe *1*, but through a deflecting lever *6* of the interference measuring head *3* (Fig. 1a). The lever has a flat surface at one end and a spherical one at the other end. Thus it can mate at the same time with both, the spherical tip of the tested probe and the flat surface of the displacement actuating system. It acts as an intermediate element which transmits the movement of the tested probe (Fig 1b). The carriage moves in a to-and-fro motion, switching the tested probe. At the moment when the probe triggers the pulse which informs about the contact, the information about travel covered by the tip between the rest point and the switching point is registered. The results are stored in a computer.

a)



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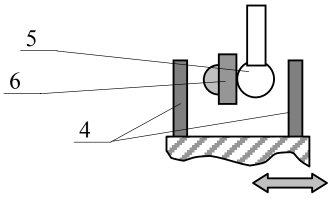

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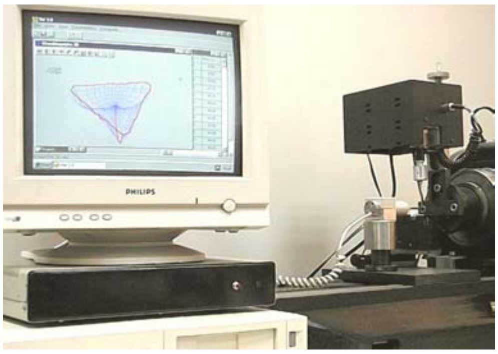


Fig. 1. Measuring set-up for triggering probes testing: a) scheme, b) detail of operation of tested probe tip with reference head, c) view.

The test set-up, equipped with a low pressure transducer, has two options of contact triggering probe testing [11]. The first option consists in testing the pretravel characteristics, its instability and repeatability. The second one additionally enables the determination of hysteresis characteristics as well as the calculation of hysteresis of the switching point, hysteresis of the rest point and hysteresis of pretravel.

3.1. Operation of the test set-up in pretravel characteristics option mode

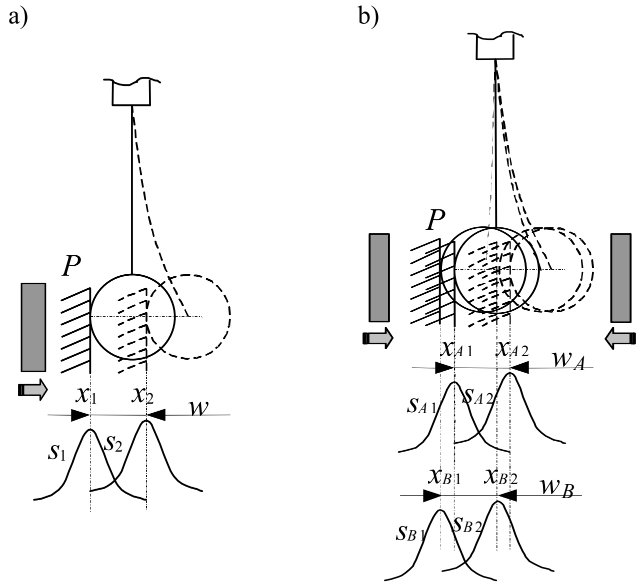


Fig. 2. Diagram of probes characteristics determination on a stand with low pressure transducer: a) option of pretravel measurement, b) option of hysteresis measurement.

The tip of the interference head *P* touches continuously the tested probe tips, measuring its position (Fig. 2a). Indication x_1 is being read at the moment of carriage withdrawal and it corresponds to the rest position of the probe tip. Then, the carriage moves in normal direction in relation to surface *P* up to the moment of contact information signal at the probe output (point

x_2). The probe pretravel w is determined as the difference of measurement head indication at rest point and probe switching point:

$$w = x_2 - x_1. \tag{1}$$

For $n2$-fold travel measurements w, its average value $\overline{w}$ is calculated. The standard deviation calculated as below is a measure of instability of the probe tip rest point calculated according to the formula:

$$s_1 = \sqrt{\frac{\sum_{i=1}^{n2} \left(x_{1i} - \overline{x}_1\right)^2}{n2 - 1}}, \tag{2}$$

where: x_{1i} - free position of probe tip in i-measurement, $\overline{x}_1$ - arithmetic average of $n2$ measurements x_{1i}.

The standard deviation is a measure of the tested probe contact opening and can be expressed by the formula:

$$s_2 = \sqrt{\frac{\sum_{i=1}^{n2} \left(x_{2i} - \overline{x}_2\right)^2}{n2 - 1}}, \tag{3}$$

where: x_{2i} - probe tip position at contact opening in i-measurement, $\overline{x}_2$ - arithmetic average of $n2$ measurements x_{2i}.

The standard deviation of pretravel s, being a measure of the determined travel value, is calculated according to the relationship:

$$s = \sqrt{s_1^2 + s_2^2}, \tag{4}$$

where: s_1, s_2 - standard deviations of position values $\overline{x}_1$, $\overline{x}_2$.

Repeatability in one direction is the maximum value of pretravel result dispersions, for any direction in space, or in a chosen transverse section. This parameter is calculated as the maximum value of double standard deviation of pretravel *max(2s)* for one measurement direction.

The repeatability as a measure of instability of pretravel is calculated following the relationship:

$$V = \max(\overline{w}) - \min(\overline{w}), \tag{5}$$

where $\overline{w}$ is the average value of pretravel for a given switching direction.

3.2. Operation of the test set-up in characteristics of switching hysteresis option mode

During measurement of tested probe hysteresis characteristics (similarly as in pretravel characteristics measurements) the interference measuring head tip P touches continuously the tested probe tip, measuring its position (Fig. 2b) [11]. The difference consists in the fact that after a reading of the rest point position x_{A1} and switching point position x_{A2}, the equilibrium condition of the contact system is disturbed by action of the switching surface in an opposite direction in respect to the measurement one. Then, a second probe switching is carried out, new positions of rest point x_{B1} and switching point x_{B2} are read.

The hysteresis of triggering point and rest point are calculated respectively from the relationships:

$$H_P = |x_{A2} - x_{B2}|, \tag{6}$$

$$H_S = |x_{A1} - x_{B1}|. \tag{7}$$

The hysteresis of pretravel is calculated as the difference of probe pretravel before w_A and after w_B equilibrium disturbance:

$$H = w_A - w_B, \tag{8}$$

where:

$$w_A = |x_{A2} - x_{A1}|, \tag{9}$$

$$w_B = |x_{B2} - x_{B1}|. \tag{10}$$

4. TESTED PROBES AND THE WAY OF TEST RESULTS ANALYSIS

Two probes of common use have been subjected to tests:

- one-stage probe with electric contact transducer, represented by TP6 Renishaw probe, and
- two-stage probe with electric contact and piezoelectric transducers, represented in tests by TP200 Renishaw probe.

The tests consisted in double measurement of: the rest point, the switching point and probe pretravel, without and with equilibrium disturbance of transducer contact system, carried out by deflecting the measuring tip in the direction opposite to the measurement direction. The instability measure of: rest point, switching point and pretravel respectively is the hysteresis of: the rest point H_S, switching point H_P and pretravel H. The measure is determined as the difference of values measured without disturbance w_A and with disturbance of transducer equilibrium condition w_B.

In the tests two rods of 50 mm length were used:

- a rod made of tungsten carbide, featuring high rigidity (low deflection rate),
- a rod made of ceramic material, with higher deflection than the tungsten carbide one and having lower mass.

The technical specification of the used rods is shown in the Table 1 underneath [8].

Table 1. Technical specification of rods used in testing.

	Tungsten carbide	Ceramic material
mass	2,52 g	0,91 g
rigidity [deflection/ pressure]	<0,25 mm/g	<0,5 mm/g

In practice it is not possible to evaluate either the wear of contact surfaces or imperfection of the electric contact transducer, these two factors being the major source of hysteresis of both triggering probe types. Neither it is possible to point out all the factors which contribute to this phenomenon. For these reasons, the derivation of a relationship which defines the hysteresis of the rest point is very difficult. However, because of the fact that hysteresis may have a substantial effect on the precision of probe operation, experimental tests were carried out. These tests consisted in measurement of the hysteresis of the switching point and pretravel, basing on two types of probes, i.e. one-stage and two-stage ones; the test target was to determine the level of the hysteresis effect on the positioning precision of the probe.

It is to be considered that there is no possibility to determine a relatively simple and practically useful relationship of the various factors contributing to the generation of the hysteresis phenomenon, i.e. measurement pressure, tip type, speed of approach to the contact. Then, in order to perform a quantitative evaluation, a statistical method of variance analysis of the above mentioned complex factors that have effect on hysteresis (ANOVA) has been used [15-17]. The method of multiple comparison was included (post hoc). All the analyses were performed using the Statgraphics statistic package [17].

The variance analysis (multiple factor type) allows to state, at a defined probability, whether the involved factors (measuring pressure, approach speed to the contact, tip type) have an effect on the given dependent variable (it this case hysteresis and pretravel). All the analyses of this work were performed with the assumption of 95% level of tests confidence. The interaction between factors has been included in the analyses. A given factor or an interaction have an essential effect on the dependent variable, in case the p-probability value for test statistics (so called p-value) is less than 0,05. The used multiple comparison (the Fisher LSD test) allowed to determine which average values for a given factor level differ from each other.

Before applying the ANOVA method, the required assumptions have been checked for all the cases. The most important ones were: normality of results distribution and equality of variance, in comparable observation groups. The first assumption has been checked using the standard tests of distribution normality (KS, Chi-square, Shapiro-Wils, skewness and kurtosis). In all the cases, the values of obtained probabilities distinctly exceeded the assumed level of test significance, thus confirming the distribution normality. The stability of group variances has been confirmed using Bartley, Chrane and Hartley tests.

5. TEST RESULTS AND THEIR STATISTICAL ANALYSIS

The carried-out tests can be split into two groups: single-stage probe tests, represented by the classic TP6 probe, and two-stage probe tests, represented by the TP200 device.

5.1. One-stage probe tests

5.1.1. Testing of effects of tip type, measurement pressure and approach speed of the measured surface on TP6 probe hysteresis.

Within the experiments using the TP6 probe, an analysis of the effect of the tested values on average values in XY plane has been performed. The values were:

- hysteresis of pretravel H
- hysteresis of rest point H_S,
- hysteresis of switching point H_P.

Additionally, an analysis of the effect of tested factors on probe hysteresis at characteristic points of the XY measuring plane has been performed. The points corresponded to:

- the minimum value of pretravel, and
- the maximum value of pretravel.

From the user's point of view, the most important factor for probe operation accuracy is **the hysteresis of the triggering point** [10, 11], as it has a direct effect on the measured element points location in the measuring space range of the coordinate machine. For this reason, considering the volume limit of the present article, the test results given below concern only selected cases of switching point hysteresis H_P.

5.1.2. Analysis of selected factors effect on the value of switching point H_P hysteresis, averaging in the XY plane

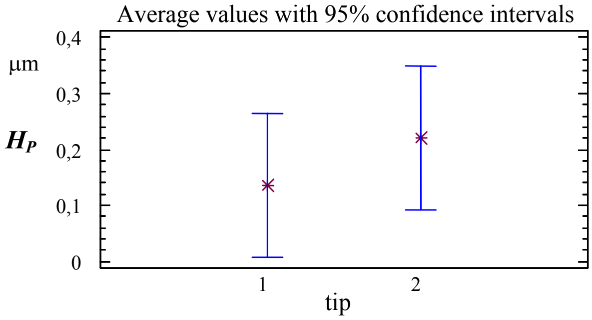
In the presented analysis, the hysteresis of the probe switching point, averaging in the whole XY plane has been selected as the dependent variable; and tip type, approach speed to the contact with the measured surface and measurement pressure have been considered as influencing factors.

The following levels of factors involved in the tests have been selected for the performed variance analysis, see Table 2.

Table 2. List of factor level values involved in the tests.

Level	*Tip*	*pressure*	*speed*
1	Tungsten carbide	4 g	3,1 mm/s
2	Ceramic material	10 g	5,0 mm/s
3	X	16 g	7,5 mm/s
4	X	X	9,6 mm/s

In the discussed case, a three-factor variance analysis has been used, considering an interaction between factors. After the performed analysis, a results table has been worked out. It is illustrated partially (main effects) by diagrams in Fig. 3.



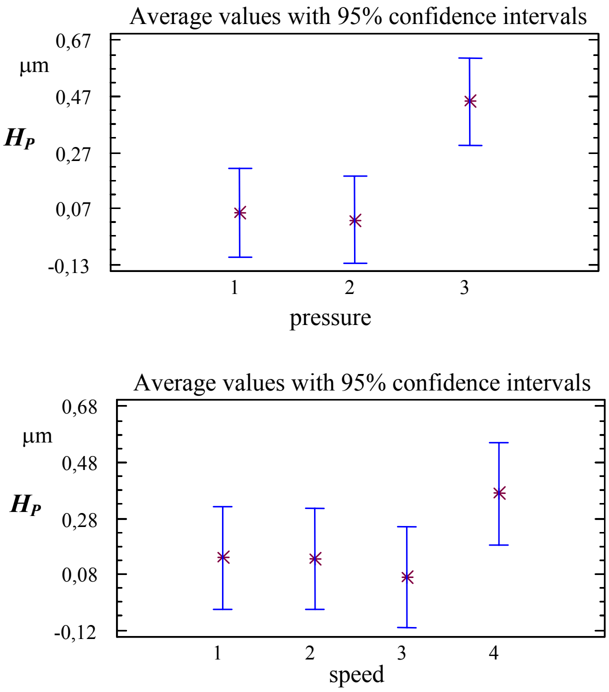


Fig.3. Hysteresis of switching point *Hp* in sequence, as a function of tip type, pressure and speed of approach to the contact.

The results given in the table confirm with a probability of 95% the essential effect of all main actions and interactions of second order between pressure and speed, and between tip type and pressure. In the latter the level of *p*-probability of test statistics is not much lower than the assumed level of significance equal to 0,05; this means that the effect is relatively weak.

Table 3. Analysis of variance for H_P.

Source	sum of squares	*Df*	variance evaluation	*F*	*p*
tip	20,0247	1	20,0247	33,17	**0,0000**
pressure	328,36	2	164,18	271,93	**0,0000**
speed	49,9336	3	16,6445	27,57	**0,0000**
tip pressure	4,09313	2	2,04657	3,39	**0,0338**
tip speed	0,31005	3	0,10335	0,17	0,9159
pressure speed	24,9389	6	4,15648	6,88	**0,0000**
tip pressure speed	3,80295	6	0,633825	1,05	0,3907
rest	2882,95	4775	0,603759		

In order to determine which main acting factors levels differentiate substantially the probe hysteresis, tests of multiple comparisons using the LSD Fisher test have been performed. The analysis results are given in Table 4.

Table 4. 95% Fisher LSD Test for H_P.

Tip level	Difference	+/- Limits
1 – 2	*-0,129193	0,0439679
Pressure level	Difference	+/- Limits

1 – 2 1 – 3 2 – 3	*-0,3201 *-0,640764 *-0,320664	0,0538438 0,0538522 0,0538522
Speed level	Difference	+/- Limits
1 – 2	*-0,19665	0,0621735
1 – 3	*-0,241333	0,0621735
1 – 4	*-0,253369	0,0621864
2 – 3	-0,0446833	0,0621735
2 – 4	-0,0567186	0,0621864
3 – 4	-0,0120353	0,0621864

* means a substantial difference

It is evidenced in the presented table that all the tip and pressure levels differentiate substantially the tested hysteresis. It results that in case of speed effect the hysteresis of the rest point for the first speed level differs substantially from other speed levels. The following diagrams in Fig. 4 show the effect of interaction on the tested hysteresis type.

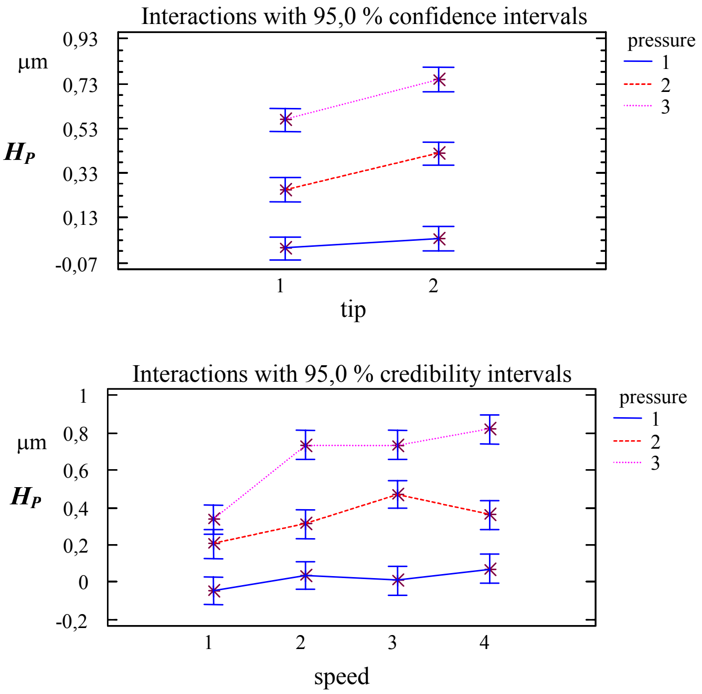


Fig. 4. Hysteresis of the switching point Hp in sequence, in function of tip type and speed level for various pressures.

5.1.3. Analysis of tested factors effect on the switching point H_P in points of maximum value of the pretravel

In the presented analysis, the average value of probe hysteresis has been selected as the dependent variable, as defined in diagram points of minimum and maximum value of the pretravel. The tip type, the approach speed to a contact with the measured surface and measurement pressure have been considered as influencing factors.

The levels of factors involved in the tests have been selected for the performed variance analysis, see Table 2. In the referred case, a three-factor variance analysis considering the interaction between factors has been used. The results for hysteresis of the switching point Hp are given in Table 5.

Table 5. Analysis of variance for Hp in points of maximum pretravel.

Source	Sum of squares	*Df*	Variance estimated	*F*	*p*
Tip	0,63001	1	0,63001	0,82	0,3657
Pressure	13,5274	2	6,76369	8,81	**0,0002**
Speed	4,63518	3	1,54506	2,01	0,1120
Tip*pressure	3,18894	2	1,59447	2,08	0,1269
Tip*speed	0,919488	3	0,306496	0,40	0,7537
Pressure*speed	1,60013	6	0,266688	0,35	0,9112
Tip*pressure*speed	5,68283	6	0,947138	1,23	0,2884
Rest	257,977	336	0,767787		

It results from the presented table that - with the exception of acting pressure - the remaining factors and interactions have a statistically negligible effect on *Hp*. It is a result close to the one for hysteresis at probe characteristic points in minimum pretravel (there additionally a speed effect appeared). However, these results differ substantially from those for hysteresis averaging in the whole plane; the effect of a higher number of effects was noticeable there.

The LSD Fisher test has evidenced substantial differences in Hp for all levels, except the first and second one. The qualitative results are shown in Fig. 4.

We point out that, notwithstanding distinct changes of Hp average values on various levels of tip and speed, the actual effect of these factors is negligible.

5.1.4. Analysis of measurement pressure and approach speed to the contact with measured surface on hysteresis of TP6 probe pretravel, in the XZ plane

Tests in the XZ plane have been performed using a tip made of tungsten carbide. During tests the probe was inclined at 0 to 72 degrees from the vertical line, in steps of 9 degrees, in defined positions corresponding to the minimum pretravel.

The average XZ probe pretravel was the dependent variable; it was determined in the point of minimum pretravel, and the approach speed to a contact with the measured surface as well as measurement pressure were considered as influencing factors.

Table 6. List of factor level values involved in the tests

Level	*pressure*	*speed*
1	4 g	3,1 mm/s
2	10 g	5,0 mm/s
3	16 g	7,5 mm/s
4	X	9,6 mm/s

The following levels of factors involved in the tests have been selected for the performed variance analysis, see Table 6. In the discussed case, a two-factor variance analysis has been used, considering an interaction between factors.

Table7. Analysis of variance for H_P in points of minimum pretravel.

Source	Sum of squares	*Df*	Variance estimated	*F*	*p*
Pressure	20,8138	2	10,4069	20,08	**0,0000**
Speed	24,2906	3	8,09688	15,62	**0,0000**
Pressure*speed	16,268	6	2,71133	5,23	**0,0000**
Rest	272,61	526	0,51827		

5.1.5. Analysis of measurement pressure and approach speed to the contact with the measured surface on the hysteresis of TP6 probe switching point, in the XZ plane

The test results for hysteresis of the switching point Hp are given below. It appears in the ANOVA table that all the analyzed factors, i.e. measurement pressure, speed and speed with pressure interactions have a substantial effect on the hysteresis of the switching point. It is a result identical with that achieved for hysteresis of pretravel.

5.1.6. Conclusions of one-stage probe tests

The performed one-stage TP6 probe tests evidenced that in most cases there is a substantial relationship between average values of the rest and switching points hysteresis and factors related to probe configuration and measurement speed.

It has been proven that the maximum value of rest point hysteresis occurs at maximum pressure, and when using a tip being more subject to elastic deformations. The speed effect is different for switching point and for rest point hysteresis. In the first case, an increase of measurement speed causes mostly an increase of the value of switching point hysteresis and causes a decrease of the value of rest point hysteresis. For this reason, the pretravel hysteresis, being a resultant of switching point and rest point hysteresis, appeared insensitive to measurement speed variation. In this case, a noticed inverse effect of the measurement speed on switching point and rest point hysteresis is being compensated. Therefore, the pretravel hysteresis response is similar to the value of pretravel response, for a one-stage probe.

The maximum value of noticed average value of one-stage probe pretravel hysteresis does not exceed 2 µm, whereas the pretravel value can have a value up to 40 µm; at the same time a significant repeatability, as far as it concerns the probe accuracy, can reach up to 25 µm. Therefore, the errors of one-stage probe operation being an effect of hysteresis are at the level of approximately 8 % of the total systematic errors of probe operation.

5.2. Two-stage probe tests

The tests of a two-stage probe TP200 (as an example) were a complement to the one-stage probe TP6 tests. There was no need to test its points of minimum and maximum pretravel value as in the case of the one-stage probe due to the fact that the two-stage probe features a circular-symmetrical characteristics of pretravel [11]. The test extent was limited by the fact that the two-stage probes are not equipped with an adjustable measurement pressure system; the latter was the main factor having an effect on one-stage probe hysteresis. Also, it results from the operation principle of two-stage probes that probe hysteresis in the XZ plane is not noticeable; our research confirms this fact. As a result, the performed tests were limited to an analysis of the effect of approach speed to the measured surface in the XY plane on three types of the hysteresis involved. The experiment scheme for all types of hysteresis has been assumed as in Table 8.

Table 8. Definition of speed levels in ANOVA analysis, at one factor experiment.

Level	Speed
1	5,0 mm/s
2	7,5 mm/s
3	9,6 mm/s

Table 9. Analysis of variance for switching point hysteresis Hp.

Source	Sum of squares	*Df*	Variance estimated	*F*	*p*
Speed	0,150169	2	0,0750847	0,62	0,5395
Rest	72,5556	597	0,121534		

ANOVA results for switching point hysteresis H_P are given in Table 9. In the analyzed case, the speed of approaching the measured surface has no relevant effect on switching point hysteresis. The diagram in Fig. 5 illustrates the qualitative interpretation.

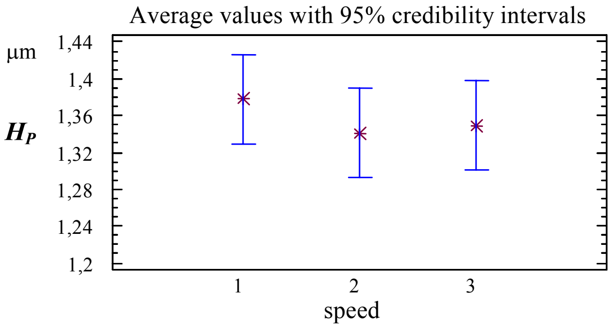


Fig. 5. Dependence of average point of TP200 probe switching on the speed level of approach to the contact.

The used variance analysis has shown in this case a substantial effect of measuring speed on the rest point and pretravel hysteresis. Instead, no significance of speed effect on switching point hysteresis level has been revealed. In cases when this effect is noticeable, the hysteresis value is higher at higher measuring speeds.

However, in case of pretravel hysteresis, its maximum value does not exceed 0,13 μm. As it has been mentioned in the introduction chapter, the most significant factor is the switching point hysteresis, from the point of view of probe accuracy during its measurement operations. The experimental tests revealed that it has a ten times higher value than the pretravel hysteresis and that it does not depend on the measuring speed. In case of the tested two-stage probe TP200, the value of switching point hysteresis does not exceed *1,4 μm*. It it a double value of pretravel instability ($V_{2D} = 0.78\ \mu m$), and a five times value of maximum no repeatability of one direction indications ($max(2s) = 0.284\ \mu m$) of this probe.

Therefore the tests whose exemplary results are given here, have shown that parameters known so far, i.e. instability and repeatability of pretravel are not sufficient to describe fully the accuracy of two-stage triggering probe operation. The experimental tests have shown that the switching point hysteresis is the major source of location errors of a two-stage triggering probe in the measuring space of a coordinate measuring machine.

6. SUMMARY

The hysteresis phenomenon of triggering probe operation is the result of direction change of measurement pressure. In case of one-stage probes, their mechanical electric contact type transducer may show imperfections of structure such as: mismatching of seats distance and movable arms, as well as motion resistance caused by friction, deformations and wear of contact surfaces. The above-mentioned factors are the cause of hysteresis and they depend on: measuring pressure, type (and mass) of tips, and switching speed.

In the two-stage probes two transducers are built in. The functioning of two-grade type transducers consists in elastic deformation. Therefore no motion resistance, caused by friction, occurs; this resistance is a major source of hysteresis in probes having a single type transducer. Anyway, the presence of an electric contact transducer in two-stage probes may be the cause of hysteresis occurrence.

Commonly used units of the TP6 type(one-stage probe) and TP200 (two-stage probe) have been selected to perform the tests. The tests were performed at various levels of factors that may affect the operation hysteresis, i.e. measurement speed, pressure and type (and mass) of tips.

In case of a tested unit of a one-stage probe it has been shown that that the highest value of rest point and switching point hysteresis appear at the highest pressure and for a tip more subject to elastic deformations. The speed effect is different for switching point hysteresis and for the rest point one. In the first case an increase of measurement speed causes mostly an increase of the switching point hysteresis value and a decrease of the rest point hysteresis value. For that reason the hysteresis of pretravel, being the result of switching point and rest point hysteresis, appears insensitive to a measuring speed variation. The observed adverse effect of the measuring speed on switching point and rest point hysteresis remains compensated in this case. Then, in this case, the hysteresis of pretravel responds similarly to the pretravel value of one-stage probes.

In addition to this, the tests of a one-stage probe have shown that pretravel, switching point and rest point hysteresis appear in both planes of probe operation (i.e. XY plane - perpendicular to the probe axis, and XZ plane - that contains the probe axis), however their participation in the total value of pretravel hysteresis is low. The maximum value of noticed average value of one-stage probe pretravel hysteresis does not exceed 2 μm, whereas the pretravel value can have a value up to 40 μm; at the same time the significant instability of pretravel, as far as it concerns the probe accuracy, can attain up to 25 μm. Therefore, the errors of one-stage probe operation, being an effect of hysteresis, are at the level of approx. 8 % of the total systematic errors of probe operation.

The hysteresis of the switching point its the most relevant from the point of view of probe operation accuracy, as it has a direct effect on locating the points of the measured element in the space of the coordinate machine. In the tested case of a one-stage TP6 probe, the hysteresis of the switching point does not exceed 0,9 μm, which is less than 4 % of other systematic errors of probe operation. It is a negligible error in comparison with another errors that affect the inaccuracy of probe operation.

The tests of hysteresis made using a second method, on a coordinate machine with a calibration procedure, have confirmed the results achieved so far. A value of hysteresis at the level 1,5 μm has been achieved using the coordinate machine. It is a value close to the one achieved on a special probe accuracy test set-up (outside of the coordinate machine). Therefore, in this case, two different research methods have evidenced the occurrence of hysteresis at the same value level.

The tests of the two-stage TP200 probe have evidenced a relevant effect of the measurement speed on values of rest point and pretravel hysteresis. Instead, no significance of speed effect on switching point hysteresis level has been revealed.

However, the maximum noticed value of pretravel hysteresis does not exceed 0,13 µm. It is a value of less than half of the random error of probe operation. The hysteresis of the switching point, being the most relevant as far as it concerns the probe measuring operation on the coordinate machine, is contributing relevantly more. The experimental tests have revealed that the hysteresis of the switching point has a ten times higher value than the pretravel hysteresis. In case of the tested TP200 probe , the value of switching point hysteresis exceeds 1,4 µm. It is twice as high as the instability of pretravel ($V_{2D} = 0.78\ \mu m$), and five times higher than the unrepeatability of one direction indications ($max(2s) = 0.284\ \mu m$) of this probe.

Therefore the tests have shown that hysteresis of the switching point is the main source of errors at locating the points by a two-stage triggering probe in the measuring space of the coordinate measuring machine.

The commonly known and used methods of testing the accuracy of probes used on coordinate measuring machines do not cover the hysteresis tests. This parameter is not considered by national or international standards concerning the coordinate measurement techniques. Also, the probe manufacturers do not include in descriptions of probe's precision the hysteresis of: pretravel, rest point and, first of all, of the switching point.

The described experimental tests have shown that the parameters known so far, given in the probe manufacturers' specifications, i.e. instability and repeatability of pretravel, are not sufficient to define fully the accuracy of probe operation, particularly of the two-stage probes. The experimental test has evidenced the hysteresis of the switching point as the principal source of errors of measured points location, carried out by a two-stage probe, in the measuring space of a coordinate measuring machine.

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BADANIA HISTEREZY SOND PRZEŁĄCZAJĄCYCH STOSOWANYCH WE WSPÓŁRZĘDNOŚCIOWYCH MASZYNACH POMIAROWYCH

Streszczenie

Współrzędnościowe maszyny pomiarowe (WMP) stanowią obecnie najnowocześniejsze urządzenia pomiarowe w zakresie metrologii geometrycznej. Większość pracujących tam maszyn wyposażona jest w stykowe sondy przełączające (impulsowe), generujące sygnał binarny w momencie zetknięcia końcówki z mierzoną powierzchnią. Niezwykle istotną sprawą jest znajomość dokładności jej działania. Jak dotąd nieznana jest histereza pracy tego typu sond i jej udział w całkowitej niedokładności pracy maszyny współrzędnościowej.

W artykule przedstawiono wybrane wyniki badań histerezy impulsowych sond dla współrzędnościowych maszyn pomiarowych. Badania dotyczyły histerezy drogi przełączania przykładowych modeli sond impulsowych jednostopniowych z przetwornikiem elektrostykowym, (którą reprezentowała sonda TP6) oraz sondy dwustopniowej z przetwornikiem piezoelektrycznym (np. TP200). W ramach przeprowadzonych testów uwzględniono wpływ długości końcówki, nacisku pomiarowego oraz prędkości dochodzenia do styku z powierzchnią mierzoną i wycofania końcówki. Do analizy wyników zastosowano metody analizy wariancji. Otrzymane wyniki w różnych warunkach i dla różnych sond zostały ze sobą porównane. W efekcie oszacowano optymalne z punktu widzenia dokładności pracy sondy wartości badanych parametrów.

Badania sondy jednostopniowej wykazały, histereza punktu przełączania stanowi pomijalny błąd w porównaniu z innymi błędami wpływającymi na niedokładność pracy sondy. Badania sondy dwustopniowej wykazały natomiast, że histereza punktu przełączania jest głównym źródłem błędów lokalizacji punktów przez sondę impulsową dwustopniową w przestrzeni pomiarowej maszyny współrzędnościowej.

Opisane w artykule badania doświadczalne potwierdziły, że dotychczas znane, podawane w specyfikacjach przez producentów sond parametry nie są wystarczające do pełnego opisu dokładności pracy sond impulsowych, szczególnie dwustopniowych. Badania wskazały na histerezę punktu przełączania jako na główne źródło błędów lokalizacji punktów przez sondę impulsową dwustopniową w przestrzeni pomiarowej maszyny współrzędnościowej.