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SIMPLE METHOD OF 3D ERROR COMPENSATION OF TRIGGERING PROBES ON COORDINATE MEASURING MACHINE

In this study an automatic, simple algorithm of systematic error corrections of a CMM touch triggering probe is proposed. The whole process does not exceed a standard calibration procedure done on coordinate machine before each measuring task. The tests show that the application of the proposed method will allow reducing fourfold the systematic errors of probe performance.

Keywords: coordinate measuring machine (CMM), triggering probe, error compensation

1. INTRODUCTION

Despite the dynamic development of scanning (measuring) probes applied in Coordinate Measuring Machines (CMM), the triggering ones are still prevailing because of low cost and relatively high accuracy. These probes generate a binary signal at the moment of touching the probe tip with the measured object's surface. The probe tip, between touching time and signal triggering, performs a travel of from a fraction up to some tenths of a micrometer. This track is called pretravel. The pretravel variation, describing the probe systematic errors caused by different switching in various directions, is one of the most important parameters of probe errors.

Over the past twenty years a remarkable progress in the coordinate measurement technology progress can be noted in electronic elements (controllers) and in the machine software. The use of modern controllers and measurement algorithms allows improving remarkably the measurement precision of a coordinate machine, and this is performed by numerical compensation of systematic errors of measuring transducers. At present, in all the coordinate machines a compensation of average pretravel is used; it is calculated during the calibration process using a master sphere, before performing the proper measurements. The effective radius of the sphere probe tip is being calculated, considering five (or more) measurement points of the master sphere; thus subtracting an average pretravel value. However, this way of determination of the average pretravel value, basing on up to a few random measuring points is not precise. This procedure does not cover information about the character of systematic errors of the probes.

Research done by Butler [1] has shown that the measuring probe is a source of 60% of errors of measurements performed on a coordinate machine, and that it is possible to improve precision by developing models of pretravel variation that consider the character of these errors. Young and Batler [2] have proposed a model of probe pretravel switching which includes a series of parameters: location of the probe in space, measuring force (usually set by adjusting the probe tip spring preload), configuration of the measurement stylus (including weight, length and rigidity of its tip), direction of switching, together with ambient conditions such as: temperature gradients, humidity and others. The authors do not present a mathematical relationship that includes all these parameters. It is reasonable, because in case of considering in the final formula all these factors; the resulting theoretical model would be a function of many parameters which are difficult to define precisely in the measurement process. Young and Batler have used neural networks to calculate the theoretical model. Basing on several learning data, an ability of generating a characteristic of pretravel by the network has been achieved; this may serve for compensation of systematic errors of triggering probes. Shen and Moon [3] have performed similar researches, by using neural networks having reverse propagation apt to correct the triggering probes errors. Following the authors, thanks to neural network use, a considerable reduction of systematic probe errors has been achieved. However, an application of such complex computing method during an actual measurement process is difficult to be carried out. The learning process of a neural network of correct model generation of probe errors is a long one, and this requires computers of high computing power.

Tyler Estler and Shen have developed a mathematical model of kinematic groups of switching probes [4, 5]. The theoretical description of a probe transducer [4] includes elastic deflections of the probe tip and a friction phenomenon which appears between the spherical tip of the measuring probe and the measured element when locating the measured points on the coordinate machine. The theoretical analysis has been limited to a simplified model of a kinematic triggering probe transducer equipped with a straight measuring tip. Theoretical researches and experimental verification has been carried out for two cases of characteristic performance cases of the tip, the horizontal and vertical ones. In case of horizontal performance, the effect of gravity of the measuring tip on pretravel characteristics has been considered. The theoretical description, as presented by Estler, considers as follows: the type of probe (structure), measuring force (intended as a preload of electric contact spring), length, diameter and rigidity of probe tip, friction coefficient between probe tip and measured element surface, gravity force of the measuring tip and direction of switching in space. The model parameters which are unknown have been calculated basing on the best theoretical function that matches the experimental researches of multiple master sphere measurements, done on the coordinate machine. The researches that confirm the presented theoretical model have been performed on a Renishaw TP2 electric contact type probe, with a measuring tip of 50 mm length. After correction of probe operating errors, a reduction of pretravel from 7.3 to 1.2 μm has been reached. Despite good results of probe operating error reduction using the theoretical model proposed by Estler, it is to be stressed that the unknown theoretical model coefficients in the analysis are numerically calculated; this calculation is carried out following the Lavenberg-Marquardt method of matching the probe error experimental characteristics [6]. However, a practical method of theoretical calculation of characteristics used in correction during an actual measuring process on a coordinate machine has not been given. Moreover, the presented theoretical model describes only one group of triggering probes, i.e. the electric contact ones. The authors did not analyze the performance of other probe types, e.g. those with a piezoceramic transducer. Further researches of Estler [5] are an enlargement of theoretical analysis of probe kinematic groups [4] and they concern the effect of inaccuracy of probe transducer manufacturing on probe metrological characteristics. This analysis covers, among other items, a non-axial action of probe transducer preload spring, and angular errors of a three arm switching transducer together with its supporting seats. The inaccuracy of probe transducer manufacturing may cause a non-axial location on the probe tip and may disturb the operating precision.

Mayer at al. [7] have shown another approach to numerical compensation of systematic probe errors. Their target was to generate a simple model, supported by a less number of possible parameters. It was assumed that the diagram of repeatability in the probe operating plane is the main characteristics that describes the precision of probe performance. The considerations assumed that during the measurement carried out on a coordinate machine, the probe tip displaces mainly orthogonally to its axis at the moment of contact with the measured object. Therefore, during switching, a slip of the spherical probe tip takes place on the switching surface. In a general case, an average condition between full slip and non slip has been taken into consideration. It was assumed that, notwithstanding the probe tip displacement trajectory, pretravel is the distance that covers the switching surface between actual touch of the measured sufrace and generation of the signal of the probe. This displacement is expressed as a function:

$$R = p(\alpha, \beta)cos(\beta) + h(\alpha, \beta)sin(\beta), \tag{1}$$

where $p(\alpha, \beta)$ and $h(\alpha, \beta)$ are vertical and horizontal components of this displacement. The authors have additionally introduced a coefficient of slip, $\lambda(\beta) = exp(-\beta/4)$. The angles α and β mean the measurement direction in space and define the participation of components in Eq. (1).

The proposed model (1) has served to correct the instability characteristics of contact triggering probe switching repeatability. This correction was carried out separately for two characteristic planes of probe performance: parallel and perpendicular to the axis. After matching the Eq. (1) to the experimental results and to the correction, a nearly fourfold reduction of repeatability has been achieved in both planes of probe performance.

Balazinski and Mayer have proposed also a fuzzy decision support system developed by the authors which allows corrections of pretravel variation [8]. The approach does not require any physical modeling of the probe and only uses measurements on the CMM's own reference sphere.

The proposed methods of correcting the systematic errors of triggering probes, as per literature [2-5, 7, 8], notwithstanding the efficiency evidenced by the authors, seem to be difficult to use in actual applications of measurement procedures on a coordinate machine. These methods require either precise definition of a series of model parameters, used per error correction, or use of neural networks or fuzzy logic and genetic algorithms that learn basing on a large number of measuring data.

The expectations of procedures correcting the systematic triggering probes errors are however different. The operator of a coordinate machine with programmed correction of probe errors is not prepared to enter values of a series of parameters. This procedure should be limited to some necessary actions that do not involve the operator and do not consume coordinate machine operation time. The present article presents a concept of simple triggering probe error correction that meets these expectations.

2. THEORETICAL ANALYSIS OF TRIGGERING PROBE PERFORMANCE

In each touch-triggering probe, the movable element must be supported at three points. The majority of used probes with supporting points have a switching transducer. It works using the principle of interrupting the internal electric contact at the moment of touching the measured object by the tip. In newly designed units, two step triggering transducers are used in order to increase probe accuracy. A classic electric contact acts then as a confirming transducer or as a protection against a fault; and another transducer (e.g. a piezoelectric one) is the proper transducer. At the moment of touching the measured object by the tip, a deformation of the piezoelectric transducer takes place. In the result the probe generates a triggering signal which causes readings on machine rulers of the localized point coordinates, and the latter are instantaneously memorized. A further displacement of machine heads together with the probe causes, at higher pressure, the generation of a second signal coming from the electric contact. This is a signal that confirms the use of the instantaneously memorized data of the measured point and stops the machine drive.

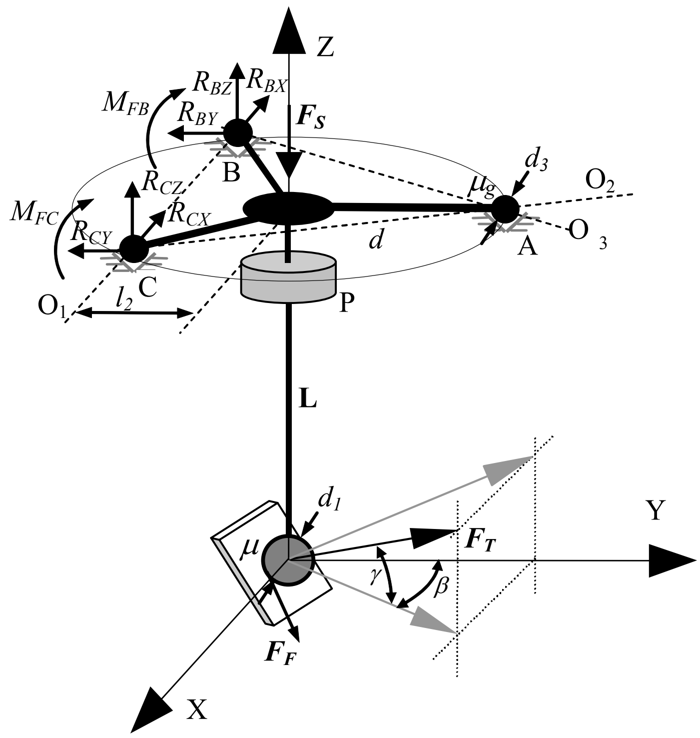


Fig. 1. Schematic diagram of triggering probe with distribution of forces.

A full analysis of triggering probe transducers (both single and two step ones), of a vertical probe or a probe inclined at an arbitrary angle, has been presented in [9, 10]. Basing on six equations of forces and moment equilibrium of the system model, as in Fig. 1, the force of probe triggering FT and the pretravel $w(\beta, \gamma)$ for various probe performance directions in space, have been calculated.

The pretravel $w(\beta, \gamma)$ is the sum of three components related correspondingly to: an elastic stylus deflection $w_E(\beta, \gamma)$, touching deflections of the probe tip and the measured surface (Hertz elastic deflection) $w_H(\beta, \gamma)$, and a switching deflection that activates the probe transducer $w_s(\beta, \gamma)$ [9]:

$$w(\beta,\gamma) = w_E(\beta,\gamma) + w_H(\beta,\gamma) + w_S(\beta,\gamma). \tag{2}$$

Finally, the resulting formula of theoretical pretravel has the following form:

$$w(\beta,\gamma) = \frac{F_S\left[\pi D^2 E\cos^2\gamma\left(l_2-\sqrt{2}\mu_g d_3\right)L^3 + 12EJ\sin^2\gamma\left(l_2-\sqrt{2}\mu_g d_3\right)L\right]}{3\pi E^2 JD^2\left[L(\cos\gamma-\mu\sin\gamma)+\underline{l_2(\mu\cos\gamma+\sin\gamma)}+\underline{\underline{\sqrt{2}\mu_g d_3(\sin\gamma-\mu\cos\gamma)}}\right]\sqrt{1-\sin^2\beta\cos^2\gamma}} +$$

$$+ A\sqrt[3]{\left(\frac{F_S\left(l_2-\sqrt{2}\mu_g d_3\right)}{\left[L(\cos\gamma-\mu\sin\gamma)+l_2(\mu\cos\gamma+\sin\gamma)+\sqrt{2}\mu_g d_3(\sin\gamma-\mu\cos\gamma)\right]\sqrt{1-\sin^2\beta\cos^2\gamma}}\right)^2\left(\frac{1}{E_1}+\frac{1}{E_2}\right)^2\left(\frac{2}{d_1}+\frac{1}{r_2}\right)}$$

$$+ \frac{2a\sqrt{L^2+d^2/3}}{d\sqrt{3}} \tag{3}$$

where: β, γ are angles that define in space the direction of probe tip movement during contact with the surface of the measured part (β - in the plane orthogonal to the probe axis, and γ - in the plane of probe axis), μ - the friction coefficient between probe tip and the measured surface, F_S - force of transducer spring, D - the diameter of a section of the measuring stylus, d - distance of probe transducer seats, d_1 - diameter of spherical probe tip, d_3 - diameter of the end of movable probe transducer arm, r_2 - curvature radius of the measured surface, at the contact point with the probe tip, L - length of the measuring stylus, l_2 - distance of the rotation axis, a - minimum opening of transducer electric contacts, necessary for probe switching, E, E_1 and E_2 - Young's modulus of stylus, tip and measured object materials, J - axial moment of inertia of stylus section, μ_g - friction coefficient in movable probe supports. The remaining symbols on Fig. 1, i.e.: F_T - triggering force, R_{BX}, R_{BY}, R_{BZ}, R_{CX}, R_{CY} and R_{CZ} - reaction components on supports B and C, M_{FB} and M_{FC} - friction moment of supports B and C, are not directly entered to the Eq. (2), and they served temporarily for calculation of the final relationship of triggering probe pretravel.

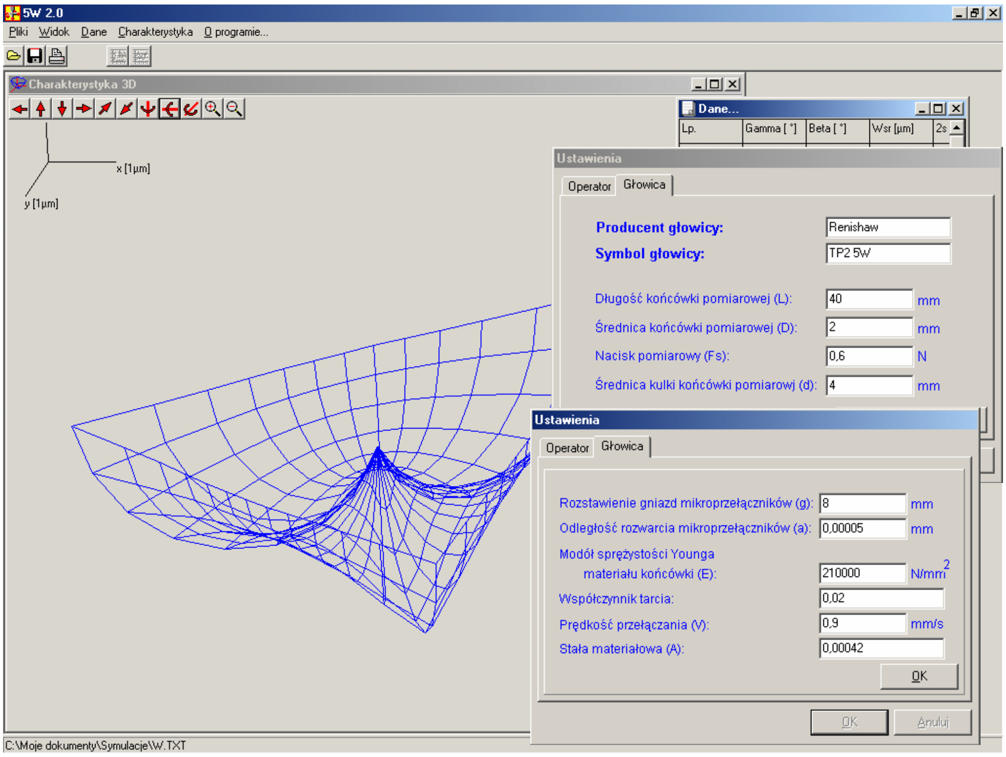
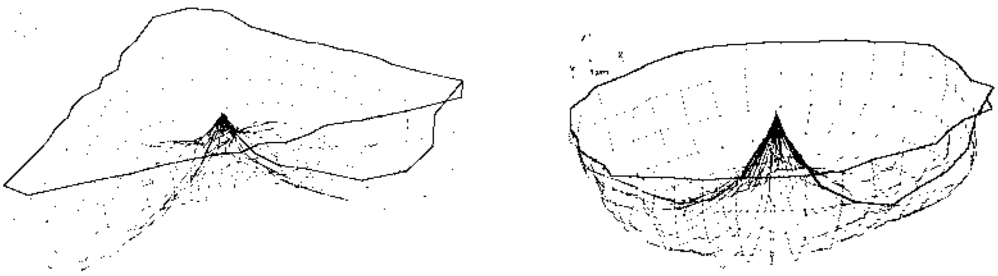


Fig. 2. Software used for simulation of triggering probe characteristic.

It is possible to calculate a theoretical, direction dependent probe pretravel characteristic basing on a model represented by Eq. (3), at given parameters of probe structure and configuration. Figure 2 presents a software window used for triggering probe characteristics simulation. The three-dimensional characteristics shown in Fig. 2 have been calculated for a Renishaw TP6 probe, equipped with a measuring tip of 40 mm length. The remaining parameters, necessary to calculate the theoretical characteristics, are shown in the figure.

3. EXPERIMENTAL VERIFICATION OF THE DEVELOPED MODEL

The presented theoretical model of triggering probe performance has been experimentally verified. A new method of measurements of probes pretravel in XYZ space, as extensively described in [10], has been used. Within the researches, measurements of full (i.e. three-dimensional) characteristics of pretravel have been carried out, for various types of probes with a single transducer of electric contact type TP1(S), TP2-5W, TP6, as well as the ones of new generation, with double piezoelectric and electric contact transducer - e.g. TP200. Fig 3a shows an example of three-dimensional characteristics, in polar co-ordinates of TP6 single stage probe, and Fig. 3b - the TP200 double stage one. The probes were tested in their standard configuration. Commonly used styluses were used. The stems were 40 mm long, 2 mm in diameter and were made of tungsten carbide with a 4 mm sapphire ball at the end. In case of probes with adjustable spring pressure the transducer thrust was set in the middle of the range. The measuring velocity of the majority of coordinate measuring machines (being also the probe triggering velocity) can be adjusted from one to a few tenths of millimeters per second. In our experiments we applied the value of 8 mm/s which is the most typical speed used for probe tests by Renishaw. Test runs comprising five measurements of the pretravel were done for each studied probe. The tip approaching direction in space was changed by 9 deg for every consecutive measurement. As the result 2000 measurement points were obtained for each probe.



a) b)

Fig. 3. Three dimensional characteristics of probe pretravel instability: a) for TP6 single stage probe, b) for TP200 double stage probe (in similar scale).

When comparing the shape of TP6 characteristics in Fig. 2 and Fig. 3a it has to be stated that there is a distinct accordance of shape of theoretical and experimental characteristics. A triangular form of diagram shape in XY plane can be explained by the three-arm structure of the triggering transducer. The diagram orientation is strictly related to the supporting point location of the transducer. In case of a probe with piezoelectric transducer (considerably more sensitive that the electro contact one), a remarkable reduction of repeatability has been noted. This is evident in Fig. 3 - and its diagram scale is similar. The shape of probe characteristics with a piezoelectric transducer is substantially different than the shape of classic electro contact probe transducer characteristics; and particularly in the XY plane, being orthogonal to the probe axis. In this section, the pretravel characteristics is approximately circular, thus contains no systematic errors of probe performance.

A quantitative acknowledgement of theoretical model accordance with statistical experimental tests, carried out for both probe types (single and double stage ones) have been shown in publications [10, 11, 12]. The calculated R-squared coefficient is not smaller than 0.85.

4. CONCEPT OF INSTABILITY CORRECTION OF PROBE PRETRAVEL

The model as described in Eq. (3) is difficult to on-line application on a coordinate machine, notwithstanding the fact that the model describes actual probe characteristics very well, as proven by experimental researches. The pretravel is a function of up to twenty parameters, and the value of some of them is difficult to evaluate. Then, the characteristics calculated following the theoretical model might be subject to an essential error. However, the developed theoretical model and researches on it, both theoretical and experimental ones, have allowed to create a simple concept of systematic probe error correction. The new method does not require additional measuring operation or calculations done by the machine operator. It does not require complicated and time-consuming calculations after every probe replacement, as it was necessary in the case of neural networks with reverse propagation [3].

A correction of probe pretravel may be carried out in the computer software based on the developed model of triggering probes pretravel (3). It has to be noted that although Eq. (3) is a function of several parameters, during a real measuring task, the system deals with a defined probe, a defined probe tip and a set spring preload. Then, all the parameters of Eq. (3), related to the probe structure and its configuration, are constant during a measurement operation on the coordinate machine. Pretravel is only a function of switching direction, defined in space by the β and γ angles. The Equation (3), after being transformed and simplified, gives a simple relationship of pretravel only as a function of β and γ angles :

$$w(\beta,\gamma)=\frac{A\cos^2\gamma}{\cos(\beta \bmod (2\pi/3))}, \tag{4}$$

where A is the equation constant. In case of probes with a piezoelectric transducer, the pretravel in orthogonal plane to the probe axis does not depend on the measurement direction β = const = 0. The resulting Eq. (4) is the basis of the proposed correction of triggering probe error.

The probe is used to locate the points of measured objects in the coordinate machine space. The triggering probes, at the moment of touching the probe tip with the object surface, generate a binary triggering signal which informs the machine about the existing touch condition. This causes a reading of coordinates from incremental transducers of the CMM measuring axis, which corresponds to the location of the probe tip, in most cases the spherical one. The determination of the actual element dimension requires considering a calibrated tip radius $r_{1cal} = d_{1cal}/2$. It is not sufficient to know the actual probe tip sphere radius, based on specification data or even on the most accurate measurements. The determined value of the sphere calibrated radius of the probe tip r_{1cal} is in fact a radius of actual tip $r_1 = d_1/2$ minus a certain value of pretravel $\overline{w}$:

$$r_{1cal}=\frac{d_1}{2}-\overline{w}\,. \tag{5}$$

In fact $\overline{w}$ is only an average pretravel which has been determined on a certain number (mostly five) of measured points of a master sphere. The value of average pretravel depends obviously on probe type and on its equipment (length, diameter and material of the stylus), or on the measuring force. However, in one measuring task these parameters do not vary.

In the most frequent case, when the sphere calibration consists of five-point measurements, and four points are located evenly on the sphere equator (every 90 deg), the fifth on the pole, the equation has a following form:

$$\overline{w}=\frac{\sum_{i=0}^{3} w(\beta=2\pi i/4)+w(\gamma=\pi/2)}{5}\,. \tag{6}$$

It is to be noted at this point that, accepting the above mentioned principle of measuring point selection, i.e. four ones located evenly on the equator and one on the pole, the calculated average value $\overline{w}$ of the pretravel remains unchanged, independently from probe location in the machine clamp and independently from the selected point of the characteristic at $\beta = 0$; this consideration remains valid for both - electric contact probes and the piezoelectric transducer ones. This is caused by the specific characteristic profile of pretravel on a plane, orthogonal to the probe axis, of both types of probe. In the case of an electric contact probe, the triangular profile of the characteristics, in a section rectangular to the probe axis, has the following properties:

$$w(\beta_i) + w(\beta_i + \pi) = C \cong const\ . \tag{7}$$

It is not possible to measure a cylinder form deviation in a section perpendicular to its axis using a similar principle. This property is evident for a probe with piezoelectric transducer, due to the theoretically circular characteristics of pretravel in a plane rectangular to the probe axis. The property (7) has been experimentally confirmed for both types of triggering probes. In the research it was stated that the value of C in relation to the β_i angle varies by some percent maximum. This instability of the C parameter results probably from random errors of probe performance.

After performing the standard probe calibration, the r_{1cal} radius is obtained, which can be written as follows, on the basis of Eqs. (5) and (6):

$$r_{1cal} = \frac{d_1}{2} - \frac{\sum_{i=0}^{3} w(\beta = 2\pi i / 4) + w(\gamma = \pi / 2)}{5}\ . \tag{8}$$

The r_{1cal} radius, determined in this way, is taken into consideration in calculations of the actual measured element dimensions. In practice, the actual d_1 diameter of the measuring tip is known with high precision. The probe tips are fabricated with high precision as well. Following the specifications of Renishaw [13], the major manufacturer of probes and equipment, the shape error of spherical measuring tips does not exceed the value of 0.15 μm. Therefore, the d_1 diameter is well known or can be accurately measured. After transformation of Eq. (8) we have the following:

$$\frac{\sum_{i=0}^{3} w(\beta = 2\pi i / 4) + w(\gamma = \pi / 2)}{5} = \frac{d_1}{2} - r_{1cal}\ . \tag{9}$$

Therefore, on the basis of a five-point measurement of the calibrated sphere, and on the basis of relation (4), the unknown value of the A constant model which defines the pretravel, can be determined for an arbitrary angular direction, this direction being defined by β and γ angles. The whole process does not exceed a standard calibration procedure done on a coordinate machine. Only an introduction of the d_1 diameter to the program is necessary; and this would be performed on the machine where the correction software is to be implemented. The scheme of the procedure of correction of triggering probe errors, based on pretravel model, is shown in Fig. 4.

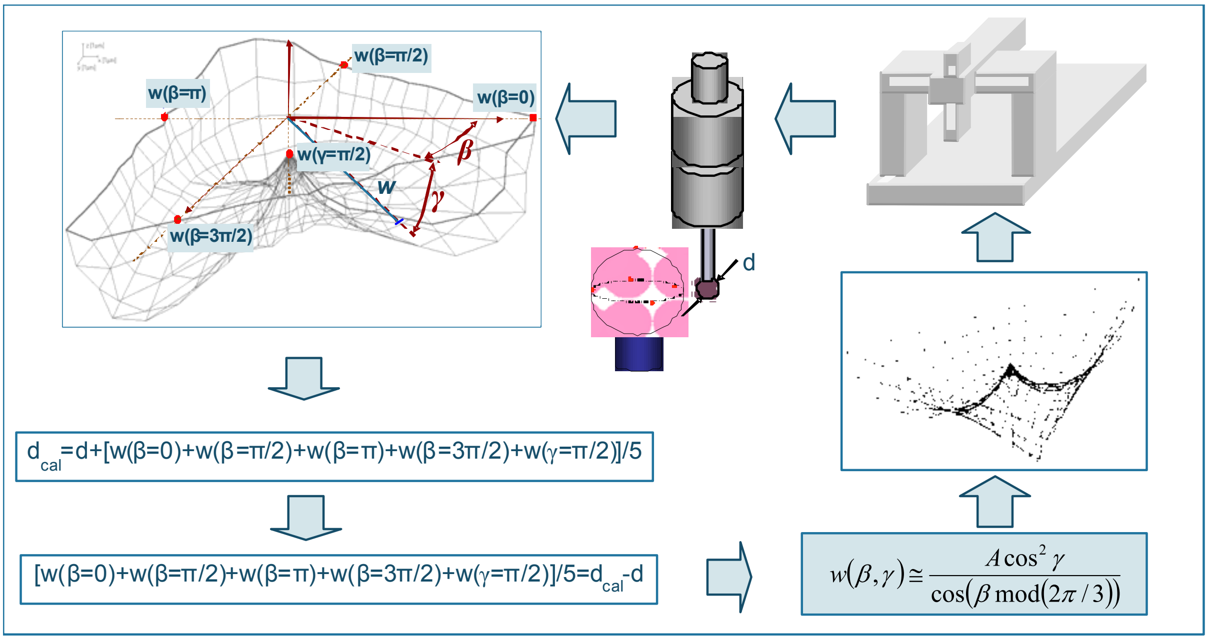
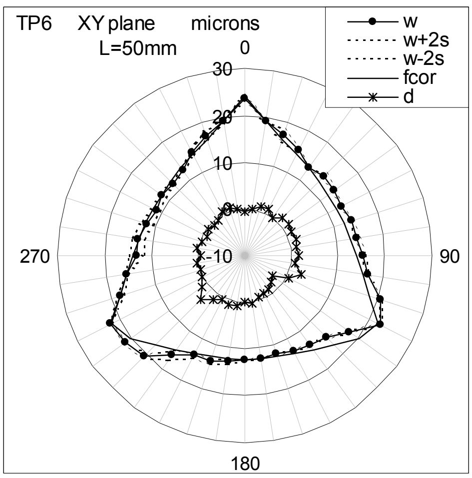


Fig. 4. Scheme of proposed triggering probe errors correction

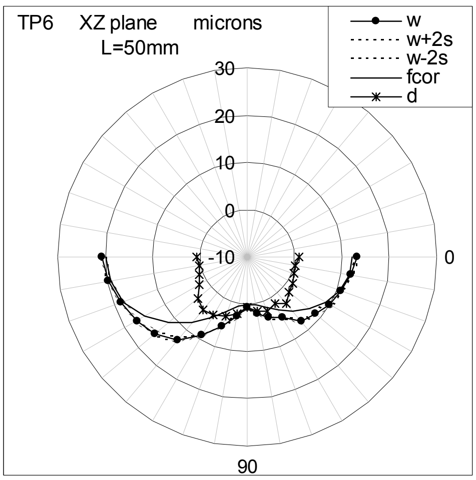
5. EXPERIMENTAL RESULTS

Experimental tests have been performed in order to check the efficiency of the proposed probe error correction. The tests were done for two types of triggering probes: a TP6 electric contact probe and a TP200 piezoelectric transducer probe, both manufactured by Renishaw, an English company. The probes were tested in their standard configuration. In case of TP6, the tests were run using two measuring styluses of 30 and 50 mm length, both 2 mm in diameter and made of tungsten carbide with a 4 mm sapphire ball at the end. In the case of TP6 probe with adjustable spring pressure, the transducer thrust was set in the middle of the range. The measuring velocity was applied with a value of 8 mm/s which is the most typical speed used for probe tests by Renishaw. Test runs comprising five measurements of the pretravel were done for each probe. The tip approaching direction in space was changed by 9 deg for every consecutive measurement. The new method of measurements of probe pretravel in XYZ space, described widely in [10], has been used.

a)



b)



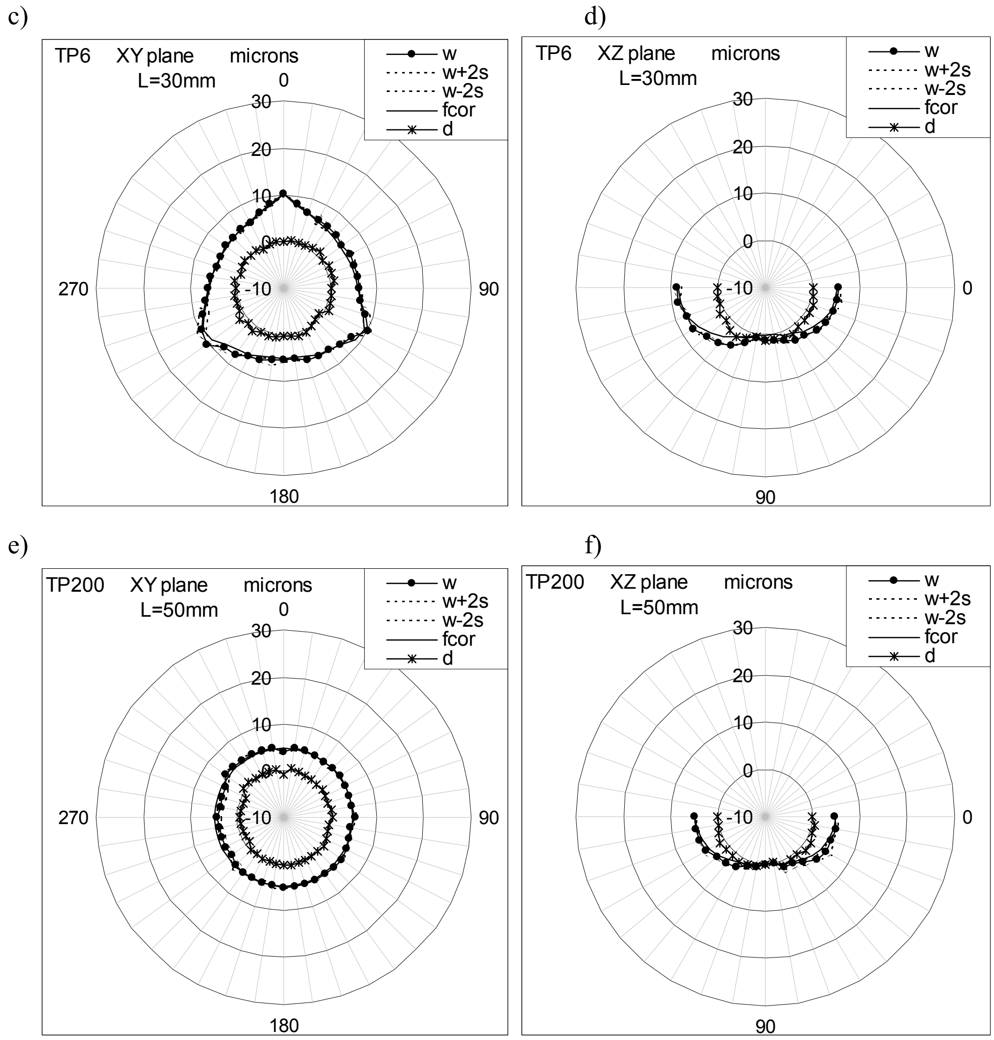


Fig. 5. Characteristics of the pretravel instability before and after correction: a) for probe TP6 with 50 mm stylus length in XY plane, b) for probe TP6 with 50 mm stylus length in XZ plane, c) for probe TP6 with 30 mm stylus length in XY plane, d) for probe TP6 with 30 mm stylus length in XZ plane, e) for probe TP200 with 50 mm stylus length in XY plane, f) for probe TP200 with 50 mm stylus length in XZ plane.

Figure 5 shows the characteristics of pretravel instability, in two sections: XY (orthogonal to probe axis) and XZ (in probe axis); the solid line with dots represents the probe performance before correction and the solid line with stars - the one after correction. The diagrams are drawn in the same scale in order to enable their comparison. The dotted lines represent an interval equal to ± double standard deviation, calculated basing on ten measurements of pretravel for each measurement direction. The solid line (with no other marks) determines a model, calculated from Eq. (4).

6. CONCLUSIONS

An automatic, simple algorithm of systematic error corrections of CMM touch triggering probes has been proposed. The whole process does not exceed a standard calibration procedure done on a coordinate machine before each measuring task. The tests have shown that the application of the proposed method will allow to reduce considerably the systematic errors of probe performance. In case of the tested TP6 probe, more than double reduction of errors has been reached, both for 30 and 50 mm measuring tips. In case of the TP200 piezoelectric type probe, the obtained reduction of systematic probe errors was more than fourfold.

ACKNOWLEDGMENT

The author is holder of a Foreign Postdoc Fellowship of the Foundation for Polish Science for a one-year visit to Polytechnique de Montréal, Département de Génie Mécanique, Centre de Recherche en Fabrication Haute Performance in Canada.

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PROSTA METODA KOMPENSACJI TRÓJWYMIAROWYCH BŁĘDÓW SOND WYZWALAJĄCYCH W URZĄDZENIU DO POMIARU WSPÓŁRZĘDNYCH

Streszczenie

Współrzędnościowe maszyny pomiarowe (WMP) są obecnie najnowocześniejszymi urządzeniami pomiarowymi w zakresie metrologii geometrycznej i są podstawowymi urządzeniami kontroli wymiarowej tam, gdzie niezbędne jest przeprowadzenie kompleksowych pomiarów, z wysoką dokładnością i w czasie dostosowanym do rytmu produkcji. Mimo ciągłego wzrostu popularności sond skanujących obecnie ciągle większość pracujących maszyn wyposażona jest w stykowe sondy przełączające (impulsowe), a w maszynach pracujących z sondami skanującymi sondy impulsowe stanowią wyposażenie wspomagające. Zespół lokalizujący punkty mierzonego przedmiotu w przestrzeni pomiarowej maszyny, jakim jest sonda, stanowi jedno z głównych źródeł błędów we współrzędnościowym procesie pomiarowym.

W artykule przedstawiono prostą metodę kompensacji błędów systematycznych stykowych sond impulsowych WMP. Procedura kompensacji błędów może być automatyczna, tzn. użytkownik współrzędnościowej maszyny pomiarowej nie musi wykonywać dodatkowych operacji pomiarowo-obliczeniowych poza zwykłą procedurą kalibracji sondy przed danym zadaniem pomiarowym.

Przedstawione w artykule wyniki badań dwóch typów sond impulsowych pokazują, że dzięki zastosowaniu opisanej procedury można uzyskać nawet czterokrotne zredukowanie błędów pracy stykowych sond impulsowych.