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MEASURING FORCE OF SCANNING PROBES OF COORDINATE MACHINES

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Abstract

The paper presents a new method, research setup and the results of the measuring force tests of active and passive scanning probes used in coordinate measuring machines. On the basis of the experimental tests, differences in the characteristics of the pressure of the measuring tip on the measured surface of the active and passive probes are described. These differences concern both the variability of the measuring force and the stabilisation time of the pressure force during the measurement. Test results can be of crucial importance, especially when measuring non-rigid workpieces.

Keywords: coordinate measurements, scanning probes, and measurement force.

1. Introduction

Currently, one of the main measurement techniques, especially in the automotive, aviation, and precision industries, is coordinate measurement technology. The number of *coordinate measuring machines* (CMM) operating in measurement laboratories and production halls is constantly growing. This is influenced by the progressive automation of the production of machine parts and devices and with it the need to adjust the rhythm of dimensional control and deviations of shape and position. The basic equipment of coordinate measuring machines is the contact probe that is used to locate the points of the measured object in the measurement space. In recent years, contact probes have also been used in *computer numerical control* (CNC) machine tools [1,2]. Thanks to this, the process of tool setting, object setting, and dimensional control of workpieces has been automated. In both cases, the primary goal is to achieve the highest possible accuracy while simultaneously increasing measurement capabilities and reducing measurement time. Therefore, since the inception of coordinate measuring technology, an intensive search has been conducted for new concepts and improvements to existing concepts related to the accuracy issues of contact measuring probes, taking into account both probe configuration and operating parameters, as well as the assessment of the uncertainty of machine geometric errors [3–6].

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Almost from the beginning of the development of coordinate measuring systems, two types of measuring probes have been developed: triggering and scanning. Scanning probes enable not only the detection of contact between the measuring tip and the surface of the measured object (like trigger probes), but also the continuous determination of the coordinates of points on the measuring surface. Scanning probes are equipped with tip displacement measurement systems, so they are in fact a micro-coordinate machine measuring the tip position in the XYZ coordinate system, usually with a resolution of 0.1 µm. During measurement, the readings from the measuring transducers of the probe are added to the coordinate values of the probe position. The sums of the readings for all three measuring axes constitute the coordinate values of the probe tip position. Unlike measurement using triggering probes, during measurement using measuring probes, the measuring tip does not lose contact with the surface of the measured object. This allows for a significant reduction in measurement time and consequently the determination of the coordinates of a larger number of measuring points.

The most used type of scanning probe with a system of flat parallel springs is shown schematically in Fig. 1a). There are three modules of spring pairs providing the measuring force (1), and three systems (2) measuring the deflection of the probe stylus (3) in three mutually perpendicular directions, X, Y and Z. In active probes, there are additional electronic force generators (4) that provide quasi-constant measuring force, regardless of the deflection of the probe stylus. Active scanning probes are most often equipped with linear optoelectronic or inductive measuring transducers.

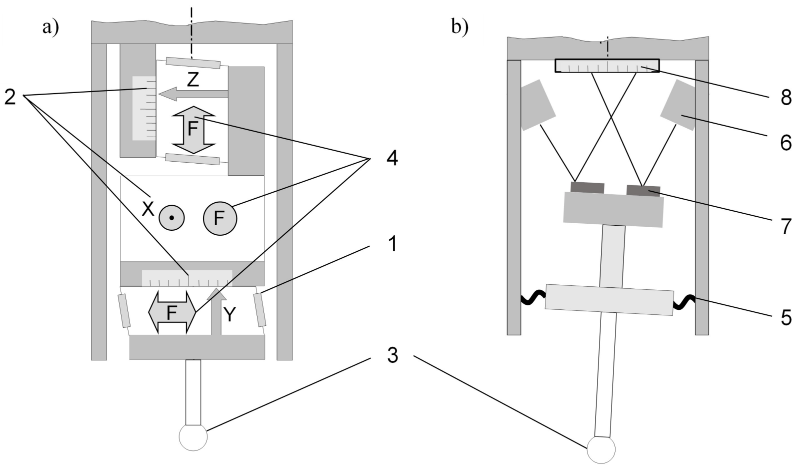

Fig. 1. Schematic diagram of the scanning probe: a) active with flat parallel spring modules, b) passive with the measuring force generated by a diaphragm spring.

In simpler and compact passive probes, the measuring force is implemented by diaphragm springs (5), as shown in Fig. 1b). The optoelectronic transducer of this probe consists of infrared beam transmitters *IRED* (6), which generate beams towards mirrors (7). The angular deflections of the mirror platform, caused by the deflection of the measuring stylus, change the position of the beam in the PSD detector (8), providing quantitative information on the measuring coordinates during scanning.

Regardless of the type of scanning probe, each of them causes the tip to press on the measured surface, causing deformations of both the measuring stylus and contact deformations of the measuring stylus and the measured surface. The effect of these forces on the measurement error is

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inversely proportional to the stiffness of the measured element but also depends on the stiffness of the measuring stylus, the diameter of the measuring stylus, and the curvature of the measured workpiece. The measuring force of the contact probe is specified by the manufacturers of both triggering and scanning probes but is specified only in the direction containing the probe axis or in the plane perpendicular to this axis for a specific stylus configuration. The problem of including the measuring force in the measurement uncertainty budget becomes crucial in the case of measuring non-rigid elements [7–9]. The methods of measuring force testing known from the literature mainly concern triggering probes used in CNC machine tools and coordinate measuring machines [10–14].

In the case of scanning probes, some experimental and theoretical investigations are conducted to facilitate the selection of stylus orientation [15] and to estimate the deformation of the measured surface [16]. The experimental investigations presented in [16] have revealed that even at low force settings, probe materials such as ruby and sapphire can cause plastic deformation in hardened carbon chrome steel.

This shows that in-depth studies of the force characteristics of scanning probes used in coordinate measurements are needed.

The aim of this paper is to present the complete measuring force characteristics of active and passive scanning probes used in coordinate measuring machines. To achieve this goal, a new automated experimental setup has been developed.

The paper has industrial and scientific applications. It is addressed to researchers and practitioners dealing with the study of accuracy of coordinate measurement systems.

2. Experimental setup

A view of the experimental setup is shown in Fig. 2. The setup consists of an executive unit for positioning and measurement (1), a computer with measurement software (2), an analogue amplifier of the force sensor (3), a 3D nanopositioner controller (4), and a NI USB-6259 data

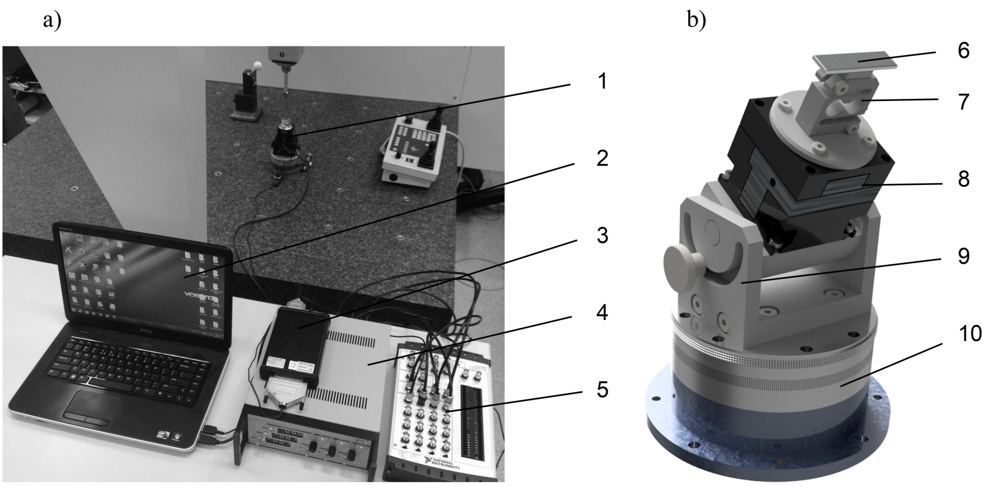

Fig. 2. View of the test setup for testing measuring force of scanning probes: a) general view of the setup, b) view of the positioning and executive unit.

acquisition card (5). The executive unit consists of a measuring surface, which is a reference plate (6) attached to a Kraftsensoren Kd24s force sensor with a measuring range of ±2 N (7). The measuring surface can be moved in the normal direction by a 3D Physik Instrumente P-611.3S nano-positioner with a measuring range of 120 μm in each axis (8). The tilting base with an angular positioning range of ±180° (9) and a rotary table with a 360° rotation range (10) allow for setting any measurement direction. The measuring force of the probe is measured during scanning the reference plate, which can be angle-positioned. The 3D nano-positioner causes the reference plate to move in the direction of its normal vector, making it possible to perform a study of the spatial characteristics of the measuring force, taking into account the dynamic effects introduced by the machine drive system.

3. Calibration of the setup and determination of measurement uncertainty

The setup was calibrated in a vertical position using M1 class weights: 20 g, 50 g, 100 g, and 200 g. For each mass, 15,000 force results were obtained from the setup of the experiment. Then a linear regression analysis was performed, which allows assessing the relationship between the force read and the one given in the form of weights. The R^2 coefficient, which defines the degree of compliance with the linear model, was 99.9688%, which confirms the linear relationship between the force read and the one given. The uncertainty of the measurement of the measuring force of the CMM scanning probes using the developed setup was calculated from:

$$u = \sqrt{u_c^2 + u_k^2 + u_w^2 + u_o^2}, \tag{1}$$

where: u_c – uncertainty related to the force sensor, u_k – uncertainty related to the data acquisition card, u_w – uncertainty related to the determination of the signal amplification factor, u_o – uncertainty of weights used during sensor calibration.

Based on data from the force sensor manufacturer and calibration performed using M1 class weights, the values of individual components of standard uncertainty were estimated:

$$u_c = 0.002 \text{ N}, \tag{2}$$

$$u_k = 3.84 \cdot 10^{-7} \text{ N}, \tag{3}$$

$$u_w = \frac{0,001 \text{ N}}{\sqrt{3}} = 0.00058 \text{ N}, \tag{4}$$

$$u_o = 0.001 \text{ N}. \tag{5}$$

Finally, the standard uncertainty of measurement of the measuring force of the CMM scanning probes using the developed setup was obtained:

$$u = \sqrt{0.002^2 + 3.84 \cdot 10^{-14} + 0.00058^2 + 0.001^2} = 0.0023 \text{ N}. \tag{6}$$

4. Results

The examination of the measuring force of scanning probes using the developed test setup was carried out on a Zeiss Accura coordinate measuring machine equipped interchangeably with two scanning probes: active (VAST Gold) and passive (VAST XXT).

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The active probe can adjust the measuring force settings within a certain range. For the tested VAST Gold probe, this range is from 50 to 1000 mN. During the tests, the measuring force was set to 200 mN. In the case of passive probes, the measuring force is not adjustable – it depends on the length of the measuring stylus, but primarily on the deflection of the probe tip during measurement.

The measurement of full characteristics of the measuring force for each of the probes was performed for two measuring stylus lengths L (70 and 150 mm for VAST Gold and 45 mm and 90 mm for VAST XXT), different measuring directions, as well as in two measuring surface simulation modes: static and dynamic. The measuring direction was changed by different angular settings of the measuring surface in relation to the probe stylus. The change of the measuring direction in the plane perpendicular to the stylus axis was carried out using the rotary table of the setup with an increment of $\alpha = 30°$ in the range of $0°-360°$, and in the plane containing the stylus axis with an increment of $\beta = 22.5°$ in the range of $0°-90°$, where angle $\beta = 0°$ means the measuring direction tantamount to the direction of the stylus axis, and $\beta = 90°$ the direction perpendicular to the stylus axis. In total, tests were performed for each of the 60 measuring directions. In each case, 15000 force measurements were recorded with a sampling frequency of 1000 Hz. Measurement of the measuring surface was carried out in the surface straightness measurement mode on a 15 mm section with a scanning speed v of 1 mm/s. Based on the tests conducted, the characteristics of the measuring force as a function of measurement time were prepared. Examples of the measuring force characteristics of the active and passive probes are shown in Figs. 3a) and 3b), respectively. For better comparison, the graphs were drawn on the same time axis scale.

Having obtained the measurement results of the measuring force characteristic for each tested measurement configuration, numerical parameters were determined, *i.e.*: $F_{\max}$ – maximum force corresponding to the tip hitting the tested surface at the moment of contact and F_{avg} – average force after stabilising the measurement (marked in Fig. 3a), $2s$ – standard deviation of the force value after stabilising the measurement on a flat surface, and, in the case of dynamic measurements using a sinusoidal surface simulator R, the range of force values.

Based on a direct comparison of the measuring force characteristics of the active probe (Fig. 3a) and the passive probe (Fig. 3b), it can be concluded that there are significant differences in both the force domain and the time domain. Regardless of the type of probe, when analysing the measuring force characteristics, three phases can be noticed: Phase I before the probe tip contacts the measured surface, Phase II of starting the contact measurement and stabilising the measuring force, and Phase III of stabilised measuring force. These phases are marked in Fig. 3. Active and passive probes differ significantly during Phase II.

In this phase, the contact of the measuring tip with the measured surface is of an impact nature. As a result, for the active probe, the measuring force value temporarily exceeds the set value almost eight times. In the initial part of this phase, the internal force regulation system tries to compensate for the reaction force of the measured surface and then stabilises it at the level of the set measurement force value. Consequently, we observe decaying vibrations with a fairly large initial amplitude. In the case of the active probe tested, Phase II, which covers the period of measurement initiation and stabilisation of the measuring force, lasts almost 2 seconds.

The design of the passive probe is much simpler because it is based on the suspension of the transducer on ordinary diaphragm springs. There are no self-regulating force systems with a feedback loop. Therefore, the measuring force should be proportional to the deflection of the measuring stylus from the resting state. Here too, the initial measuring force value increases momentarily but stabilises much faster, after less than 1 second from the start of the measurement.

Tables 1 and 2 show collective graphs of the maximum measuring force $F_{\max}$ (dotted line), the average force F_{avg} (continuous line) and the double standard deviation $2s$ (dashed line) of the force value after stabilising the measurement on a flat surface for two stylus lengths and different

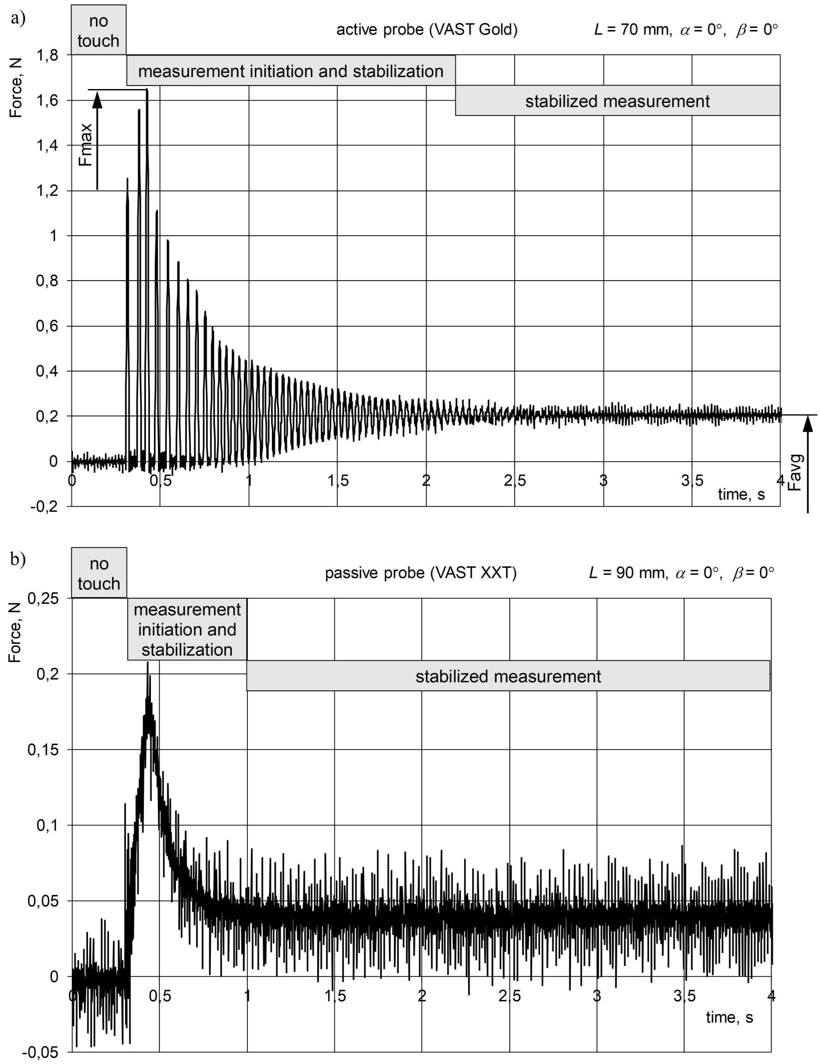

Fig. 3. Examples of time-domain measurement force characteristics of the probe: a) active, b) passive.

measuring directions of the active and passive probes, respectively. In the case of angle $\beta = 0°$ (measurement direction consistent with the direction of the stylus axis), a single characteristic is tested, which does not depend on angle α.

In the case of the active probe, it is for the angle $\beta = 0°$ that the greatest difference occurs between the maximum measuring force F_{max} and the average measuring force F_{avg} after stabilising the measurement. The smallest difference in the values of these forces occurs for the angle $\beta = 45°$, however, for this angle the average measuring force F_{avg} after stabilising the measurement differs the most from the set measuring force (200 mN). The general shape of angular characteristics in the plane perpendicular to the axis of the active probe stylus is quasi-circular and does not differ much depending on the length of the measuring stylus used.

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Table 1. Maximum measuring force $F_{\max}$, the average measuring force F_{avg} and the double standard deviation $2s$ of the force value after stabilising the measurement on a flat surface for two stylus lengths and different measurement directions of the active probe.

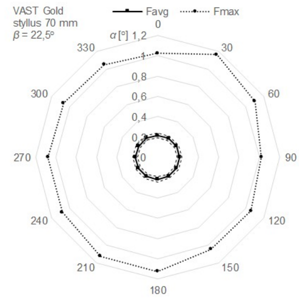
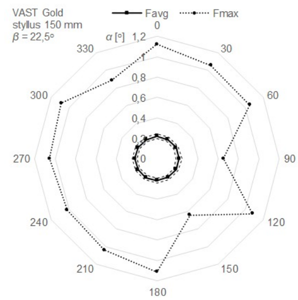
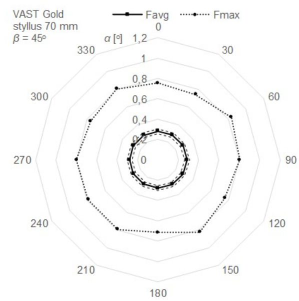
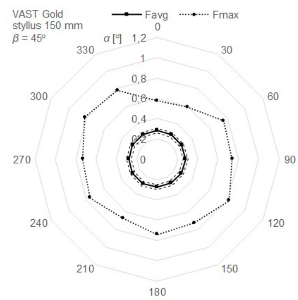
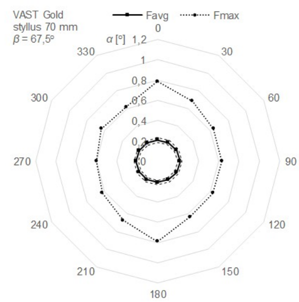
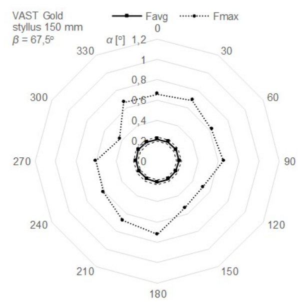
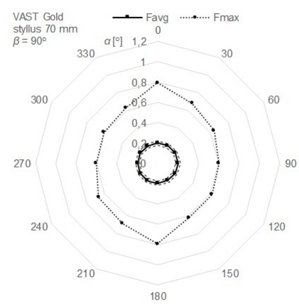
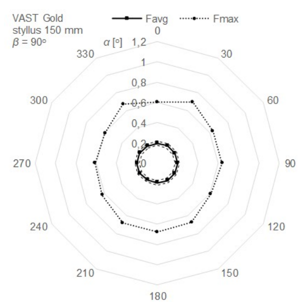
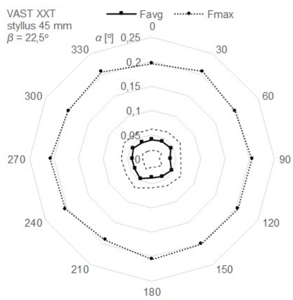
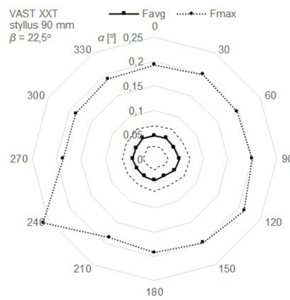
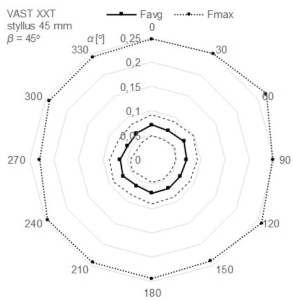
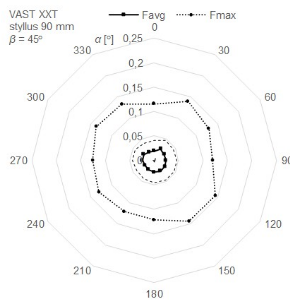
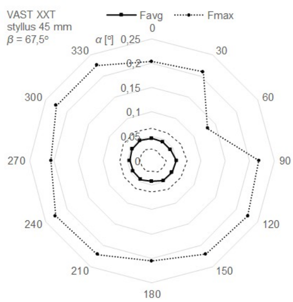
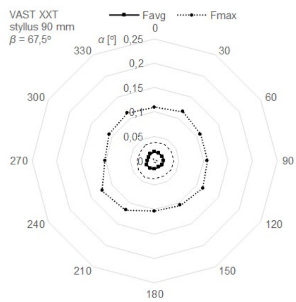
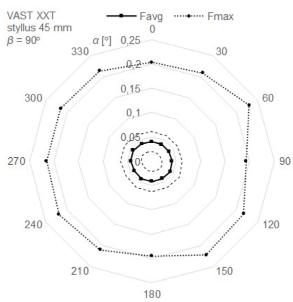
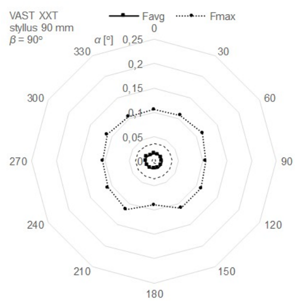
β [°]/L [mm]	70	150
0	$F_{\max}$ = 1.654; F_{avg} = 0.203; $2s$ = 0.023 [N]	$F_{\max}$ = 1.553; F_{avg} = 0.202; $2s$ = 0.023 [N]
22.5		
45		
67.5		
90		

Table 2. Maximum measuring force $F_{\max}$, the average measuring force F_{avg} and the double standard deviation $2s$ of the force value after stabilising the measurement on a flat surface for two stylus lengths and different measurement directions of the passive probe.

β [°]/L [mm]	45	90
0	$F_{\max}$ = 0.213; F_{avg} = 0.039; 2s = 0.022 [N]	$F_{\max}$ = 0.218; F_{avg} = 0.038; 2s = 0.022 [N]
22.5		
45		
67.5		
90		

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The characteristics of the measuring force of the passive probe shown in Table 2 differ depending on the length of the measuring stylus. Only in the case of measurements in the direction of the stylus axis (for angle $\beta = 0°$) are the differences small. Changing the measurement direction towards the plane perpendicular to the stylus axis increases these differences. In the case of a longer stylus, we observe a significant reduction in both the maximum measuring force $F_{\max}$ and the average measuring force F_{avg} compared to the probe equipped with a shorter stylus for measurement. This phenomenon is easily explained by the behaviour of the moment of force. With an increase in the length of the arm, the value of the force decreases. The general shape of the angular characteristics in the plane perpendicular to the axis of the passive probe stylus is also quasi-circular.

In the dynamic mode, the flat measuring surface of the test setup, shown in Fig. 2, performed a sinusoidal movement in the direction normal to the measuring surface. The displacement amplitude value was 50 µm, and the frequency was 0.5 Hz making it possible to test the stability of the measuring force during the measurement of a dynamically changing measuring surface.

Analysis of the characteristics of the active probe's measuring force allows us to state that in the case of measurements of surfaces with variable curvature, the range of force variation is large and reaches ±50% of the set value, and in the case of an angle of $\beta = 45°$, the entire field of force variation is shifted in such a way that the differences reach +100% of the set value. The smallest variation of the measuring force occurs during measurement in the direction perpendicular to the stylus axis (for an angle of $\beta = 90°$). There is no visible effect of the stylus length on the measuring force characteristics of active probes.

In the case of a passive probe, the relative variability of the measuring force is even greater during dynamic measurements. The measuring force varies from almost zero (risk of tearing the tip off the measured surface) to up to 3 times the average value. The force characteristics are strongly dependent on the length of the measuring stylus. For a longer stylus and measurement in the direction perpendicular to the stylus axis (for angle $\beta = 90°$), the average measuring force is twice as small as the average measuring force for the direction along the stylus axis (for angle $\beta = 0°$).

5. Conclusions

The paper presents the method and results of the measuring force tests of active and passive scanning probes used in coordinate measuring machines. Based on the experimental tests, the differences in the characteristics of the measuring tip's pressure on the measured surfaces of the active and passive probes are described. These differences concern both the variability of the measuring force and the stabilisation time of the measuring force during the measurement process.

In the case of each contact measurement, the start of the measurement (from the contact of the measuring tip with the measured surface) is of an impact nature. In this phase, in the case of the active probe, the measuring force value momentarily exceeds the set value by almost eight times, and the stabilisation time of the measuring force is almost 2 seconds. In the case of the passive probe, stabilisation of the measuring force takes less than half the time, however, the value of the measuring force, even after stabilisation, strongly depends on both the measuring direction in the plane containing the probe axis and the length of the stylus. The measuring force values can differ many times. Considering the presented studies, a further question should be asked: how does the variability of the measuring force during measurements with an active and passive probe affect the measurement error. The answer to this question can be obtained by calculating the deflections of the measuring stylus and the Hertzian elastic deformations resulting from the interaction of the ball of the probe tip with the measured surface for the obtained courses and characteristics of the measuring force. Such studies are extensive and may be the subject of another article related to the topic.

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