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INCREASING THE POSITIONING ACCURACY OF THE FEED KINEMATIC LINKAGES OF CNC MACHINE TOOLS THROUGH THE CALIBRATION METHOD

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Abstract: The accuracy of a CNC machine tool is one of the most important parameters that make the geometry and dimensions of the work pieces comply with the tolerance limits specified through the designer’s technical drawing. When a machine tool is handed over to the customer it is compliant in terms of the accuracy limits specified in the documentation but, after a time interval of usage, because of the wear of the components in relative motion and machine exploitation conditions. This work suggests an innovating method of testing the accuracy of a CNC machine tool by using the “calliper”, with a view to enhancing the positioning accuracy of the feed kinematic linkages. After designing and manufacturing this device, the measurement of the target points on the coordinate measuring machine is necessary, so that this device becomes a “calliper”. For inspecting the machine tool, the “calliper” is located on the machine table, being measured at the target points by means of the probe with the tactile shooter that belongs to the machine. The measurement results are stored and compared to the results of the measurements performed through the coordinate measuring machine. In function of the two measurements the related corrections of the errors will be done in the software of machine tool numerical control.

Key words: positioning accuracy, CNC machine tools, feed kinematic linkage, “calliper”, machine tool errors.

1. INTRODUCTION

The modern machining process of the work pieces on computerized numerically controlled (CNC) machine tools requires a high productivity as well as an increased accuracy of the machined work pieces. In order to comply with such conditions, CNC machine tools need to be properly maintained, through periodical technical checking, correlated with recalibrations of the machining axes such as to obtain a machining accuracy that ranges within the requirements specified by the machine tool builder. These maintenance processes are, in general, large consumers of time and resources, since they require qualified personnel and specialized equipment such as: laser level gauge, autocollimator, ball bar, laser interferometer and, newer, Laser Tracker. Even so, the CNC machine tool monitoring is necessary on a time basis, by making use of various techniques for the error sources that are generators of imprecision, to be removed [1]. The error generating sources are various and these may affect, trough the errors being induced, the machining process of the machine tools. To the category of external error sources, the error sources coming from machine tool environment are belonging, such as: temperature differences from day to night, from a season to another, the gravity forces of the machine components and table load, as well as the vibrations generated the neighbouring machines. The internal error sources are based on inexactnesses in the inner structure of the machine tool that, during the machining process will generate various errors that will reflect into the profile of the machined work piece. Such errors may come from: misalignment of the components that generates geometrical and kinematical errors [2]; heat propagation from several components of the machine structure that leads to thermo-mechanical errors [3, 4]; forces generated during the cutting process [5]; the servo-control system of each controlled axis. Another source of geometrical errors, frequently encountered on CNC machine tools comes from the accidental buffering of the machine moving parts because of operators’ lack of attention; this requires an immediate verification of the machine because its geometry might be affected and a recalibration of the axes might be needed. All these error generating sources are to affect the accuracy of the machine tool during the cutting process. More exactly, during the interpolation of the machine axes for performing the contours, such errors will lead to position deviations of the tool tip in relation to the work piece. This deviation is also variable and will be found on the entire working space of the machine tool and it will influence the dimensional accuracy of the work piece mechanically processed [6].

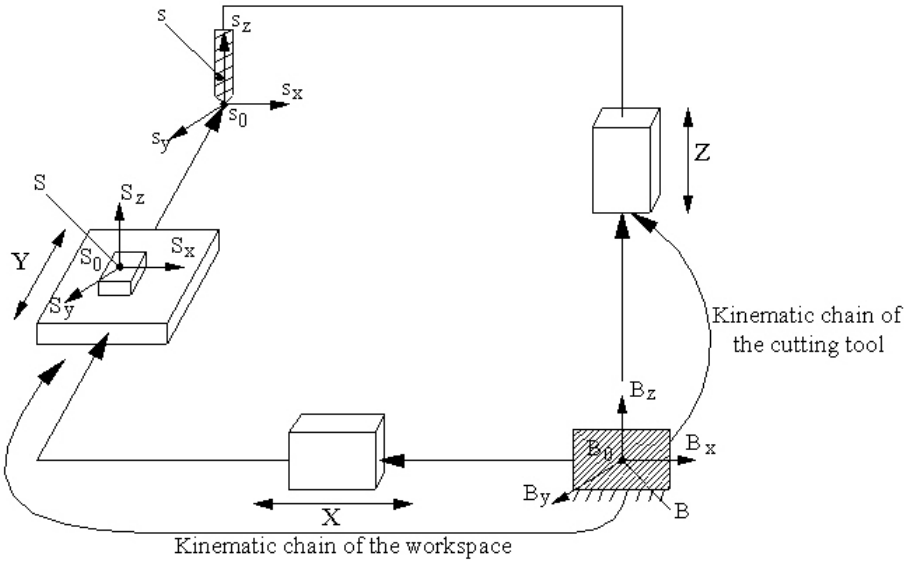

Fig. 1. Kinematic linkage and relation between axes on the CNC vertical machining centre

2. SETTLING THE KINEMATICAL PATTERN

In order to settle the kinematical pattern, it is, first of all, necessary to determine the kinematical linkage of the machine tool, as per Figure 1. For a vertical machining centre the kinematical linkage is composed of three translation axes: two horizontal ones, *X* and *Y* and a vertical one, *Z*. On the horizontal axes *X* and *Y* the machine table is superposed and *Z* axis corresponds to the machine spindle that includes the cutting tool. As such, the topology of this kinematic linkage can be established, being represented as *[SXYBZs]*, where: *X*, *Y* and *Z* – components of the translation axes; *S* – working space; *B* – bed; *s* – cutting tool. Each main component of the kinematical linkage has its own coordinate system that accompanies the respective component and, during its motion, six degrees of freedom will be recorded. By having three main components there will exist eighteen freedom degrees, to which three more relative motions between the main components will be added, i.e. the perpendicular deviations between the *X*, *Y* and *Z* axes. In this case the system will have a total of twenty-one freedom degrees, reified through errors of the machine tool. With the help of the kinematical pattern the errors of the main components corresponding to the coordinate systems of the three axes can be combined, in order to create a global coordinate system that is fixed to the basic structure of the machine tool, i.e. on the machine bed.

The vector *s* is defined that belongs to the local coordinate system of the component *Z*: $s = [s_x, s_y, s_z]$; this is the reference point of the cutting tool in the working space. The numerical control of the machine tool, through its position canned cycle, has the capacity to detect the position of the tool tip. This can be done by relating the coordinate system of *Z* axis to the coordinate system of *X* axis noted s_{MZ}. This is a homogenous transformation matrix of the coordinate system of *Z* axis into the coordinate system of *X* axis. The local coordinates of *Z* axis will be, in this case, accompanied by errors that are noted as $E_Z = e_{ZX}, e_{ZY}, e_{ZZ}, \alpha_{ZX}, \alpha_{ZY}, \alpha_{ZZ}$.

Moreover, in order to establish the position of the tool tip, it is necessary to know the reference coordinates of the machine tool bed B_{MX}, that, on their turn will have the errors $E_X = e_{XX}, e_{XY}, e_{XZ}, \beta_{XX}, \beta_{XY}, \beta_{XZ}$. With the help of the homogenous transformation matrix the position of the cutting tool tip P_s may be obtained according to the relation (1):

$$P_s = \begin{bmatrix} X_s \\ Y_s \\ Z_s \\ 1 \end{bmatrix} = s_{MZ} \cdot E_Z \cdot B_{MX} \cdot E_X \cdot \begin{bmatrix} s_x \\ s_y \\ s_z \\ 1 \end{bmatrix} \tag{1}$$

Where: P_s – the reference point of the cutting tool within the machine working space; s_{MZ} – position of the cutting tool tip; E_Z –*Z* axis errors; B_{MX} – machine bed position in relation to *X* axis; E_X – *X* axis errors; s_x, s_y, s_z – local coordinates of the cutting tool.

Similarly, the target position on the working surface may be obtained, by marking a vector $S = [S_X, S_Y, S_Z]$, that has the reference coordinates on *Y* axis of the machine tool. The homogenous transformation matrix for *Y* axis will be defined as being $B_{MY} \cdot E_Y$, where E_Y are the error elements of *Y* axis, $E_Y = e_{YX}, e_{YY}, e_{YZ}, \gamma_{YX}, \gamma_{YY}, \gamma_{YZ}$. As such, the target position on the working surface P_S may be written according to the equation (2):

$$P_S = \begin{bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{bmatrix} = B_{MY} \cdot E_Y \cdot \begin{bmatrix} S_X \\ S_Y \\ S_Z \\ 1 \end{bmatrix} \tag{2}$$

where: P_S – target position on the working surface; B_{MY} – bed position in relation to *Y* axis *Y*; E_Y – *Y* axis errors; S_X, S_Y, S_Z – local coordinates of the working surface.

Because of thee errors of the axis components, the position of the cutting tool will be deviated in relation to the target position on the working surface. By defining an error vector $\Delta_e = [e_X, e_Y, e_z]$, the relative displacement may be derived, as per the relation (3):

$$\Delta_e = \begin{bmatrix} e_X \\ e_Y \\ e_Z \\ 1 \end{bmatrix} = \begin{bmatrix} X_s \\ Y_s \\ Z_s \\ 1 \end{bmatrix} - \begin{bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{bmatrix} = P_s - P_S \tag{3}$$

Where Δ_e – variation of the cutting tool tip in relation to the working surface.

By means of the kinematic modelling, the real position of the cutting tool may be determined in relation to the work piece, but the identification of the errors through the current methods is difficult. For this reason, this research proposes the implementation of a new measuring and compensation method of the machine tool errors by making use of a calibrated device.

3. THE MEASURING DEVICE

The need for enhancing the positioning accuracy on CNC machine tools comes up when such machine tools record various wear degrees of the components in relative motion or when the inner and external temperatures provoke thermo-mechanical deformations of the machine components. This may also come up when accidental buffers are happening between the cutting tool and the work piece. Such situations lead unavoidably to modifying the CNC machine tool geometry.

In order to succeed in remedying the positioning accuracy in a relatively short time, a new method is proposed that consists of correcting the machine tool errors based on an innovating device to which the measurement of the machine axes can be related. This measuring device, further on named "calibre", is the reference unit used in this research for enhancing the positioning accuracy of the CNC machine tools. The calibre is made of an aluminium body of the dimensions 500x500 mm, on which five rails made of the same material are fixed and each rail features five bores of Ø20 mm diameter.

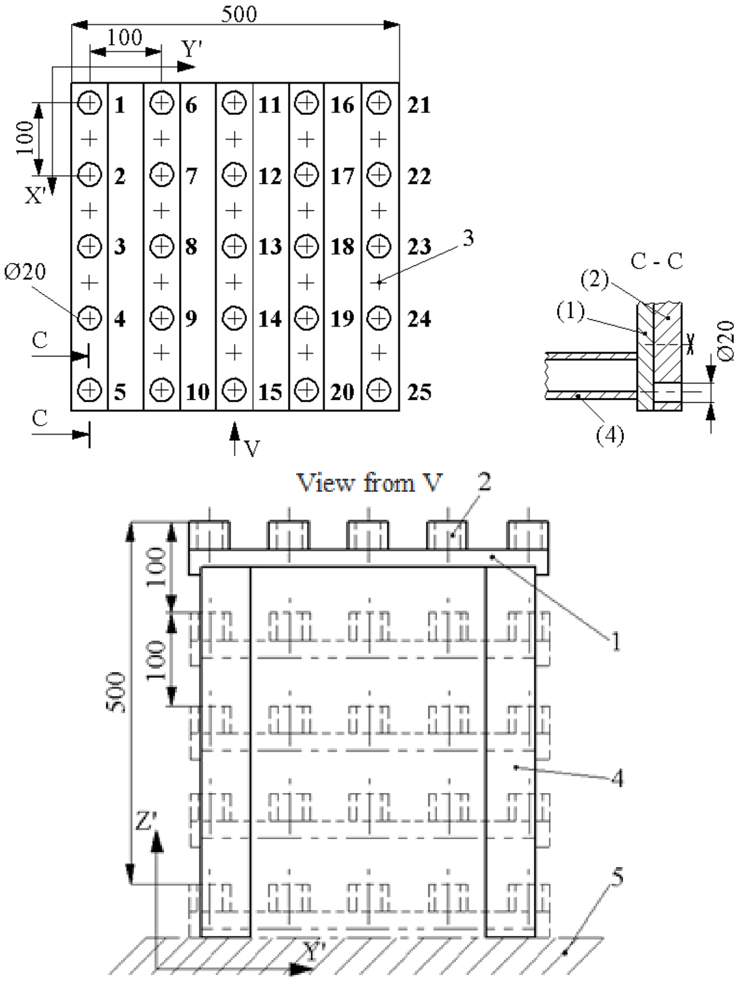

Fig. 2. Calibrated device: 1- calibre body; 2- rail; 3- screw; 4- leg; 5- machine table

These five rails are fixed to the calibre body by means of four screws, as shown at Figure 2. For positioning the calibre in the entire working space of the 4x4 legs (supports) made of square pipe (Al alloy), are used. These are made in segments of 100; 200; 300 and 400 mm length. After the calibre is designed and manufactured, it will be submitted to measurements on the coordinate measuring machine with a view to establishing the reference values. For this purpose, five sets of measurements will be carried out, for all milestones in the five positions of the working space, according to Figure 2. For each set of measurements there will be 25 spatial points of the calibre. Each spatial point has three coordinates (X, Y and Z), that can be obtained by measuring, through a touch probe, five marked points (a, b, c, d and e) as per Figure 3, where X and Y mean the coordinates of the Ø20 mm bore centres.

By repositioning the calibre with the help of the legs, five positions will be obtained eventually in the entire working space of the machine, materialised through five sets of reference data for 25 spatial points each, finally counting 125 spatial reference points in the working volume of the machine tool.

4. EXPERIMENTAL TRIALS

The experimental trials have been performed on a vertical milling centre CPV-500, featuring the following axis travels: X=500 mm; Y=500 mm; Z=450 mm. The machine model CPV-500 has 15 years of usage and during the last 3 years it was not submitted to interventions on geometry and positioning accuracy on the three numerically controlled axes.

After its designing, manufacture and measurement of the reference coordinates on the coordinate measuring machine, the measuring device that became calibre is submitted to experimental trails on the CNC machine tool where the points of interest will be measured by means of a touch probe that is in the CNC machine tool endowment.

In order to cover the entire working space of the machine four more repositions of the calibre are necessary and these are done by inserting the 4x4 legs of lengths 100; 200; 300 and 400 mm. At a first stage the data of the coordinates (*X*, *Y*) of the Ø20 mm bore centres have been collected from the 25 measuring points of the device. Measurements have been performed on a 3D Mitutoyo coordinate measuring machine, based on a program. The second stage continued on the coordinate measuring machine as well, by measuring the dimension *Z* of the 25 points having the tester positioned in relation to *X* and *Y* previously measured. The values of these dimensions may be found in Table 1. Thus, the device becomes “calibre” for the measurements of the machine model CPV-500. The measurement begins with the installation of the calibre on the CPV-500 machine table; afterwards, based on a program, by following the same two steps, the coordinates *X*, *Y* and *Z* of the 25 points of the device will be measured, as per Table 2.

The compensation values are reified through the errors of each axis, so that: $\Delta X_{1\rightarrow 25}=X_{1\rightarrow 25} - X'_{1\rightarrow 25}[mm]$; $\Delta Y_{1\rightarrow 25}=Y_{1\rightarrow 25} - Y'_{1\rightarrow 25}[mm]$; $\Delta Z_{1\rightarrow 25}=Z_{1\rightarrow 25} - Z'_{1\rightarrow 25}[mm]$, values that may be found in Table 2.

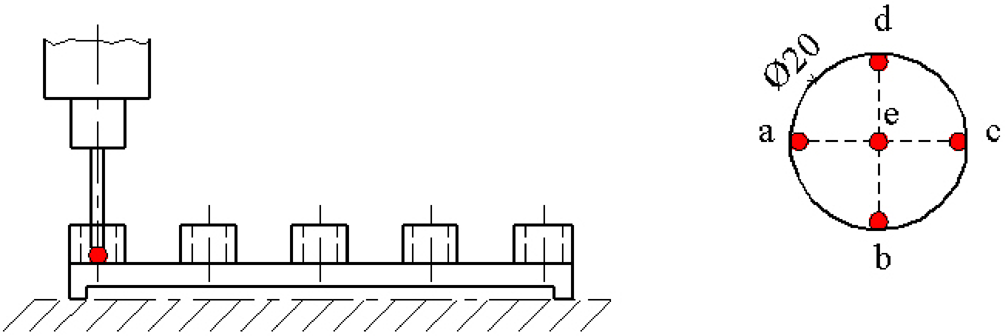

Fig. 3. Points of interest where measurements are performed

Table 1. Values of the device measurements

Nr. Ctr.	*X [mm]*	*Y [mm]*	*Z [mm]*	Nr. Ctr.	*X [mm]*	*Y [mm]*	*Z [mm]*
1	100.0313	100.0443	100.0202	14	400.0389	300.0348	100.0236
2	200.0325	100.0412	100.0211	15	500.0398	300.0381	100.0244
3	300.0341	100.0494	100.0218	16	100.0322	400.0492	100.0202
4	400.0368	100.0421	100.0229	17	200.0344	400.0477	100.0231
5	500.0393	100.0456	100.0241	18	300.0379	400.0432	100.0247
6	100.0321	200.0472	100.0193	19	400.0390	400.0446	100.0252
7	200.0323	200.0453	100.0206	20	500.0421	400.0488	100.0267
8	300.0359	200.0402	100.0221	21	100.0327	500.0493	100.0216
9	400.0378	200.0425	100.0232	22	200.0339	500.0485	100.0233
10	500.0402	200.0388	100.0239	23	300.0372	500.0442	100.0245
11	100.0342	300.0377	100.0185	24	400.0396	500.0467	100.0278

12	200.0339	300.0356	100.0199	25	500.0412	500.0506	100.0299
13	300.0375	300.0334	100.0223	-	-	-	-

Table 2. Measurement values after calibration and axis compensations

Nr. Ctr.	*X' [mm]*	*Y' [mm]*	*Z' [mm]*	*X-X' [mm]*	*Y-Y' [mm]*	*Z-Z' [mm]*
1	100.012	100.039	100.019	0.0193	0.0053	0.0012
2	200.013	100.031	100.021	0.0195	0.0102	0.0001
3	300.015	100.039	100.025	0.0191	0.0104	-0.0032
4	400.016	100.026	100.029	0.0208	0.0161	-0.0061
5	500.016	100.024	100.031	0.0233	0.0216	-0.0069
6	100.013	200.028	100.016	0.0191	0.0192	0.0033
7	200.014	200.026	100.020	0.0183	0.0193	0.0006
8	300.019	200.021	100.026	0.0169	0.0192	-0.0039
9	400.021	200.022	100.031	0.0168	0.0205	-0.0078
10	500.027	200.017	100.032	0.0132	0.0218	-0.0081
11	100.015	300.029	100.015	0.0192	0.0087	0.0035
12	200.019	300.025	100.019	0.0149	0.0106	0.0009
13	300.022	300.022	100.024	0.0155	0.0114	-0.0017
14	400.026	300.019	100.026	0.0129	0.0158	-0.0024
15	500.027	300.015	100.028	0.0128	0.0231	-0.0036
16	100.013	400.028	100.018	0.0192	0.0212	0.0022
17	200.016	400.035	100.023	0.0184	0.0127	0.0001
18	300.022	400.029	100.026	0.0159	0.0142	-0.0013
19	400.026	400.027	100.029	0.013	0.0176	-0.0038
20	500.028	400.026	100.031	0.0141	0.0228	-0.0043
21	100.011	500.039	100.025	0.0217	0.0103	-0.0034
22	200.014	500.034	100.023	0.0199	0.0145	0.0003
23	300.021	500.026	100.026	0.0162	0.0182	-0.0015
24	400.025	500.027	100.031	0.0146	0.0197	-0.0032
25	500.029	500.028	100.035	0.0122	0.0226	-0.0051

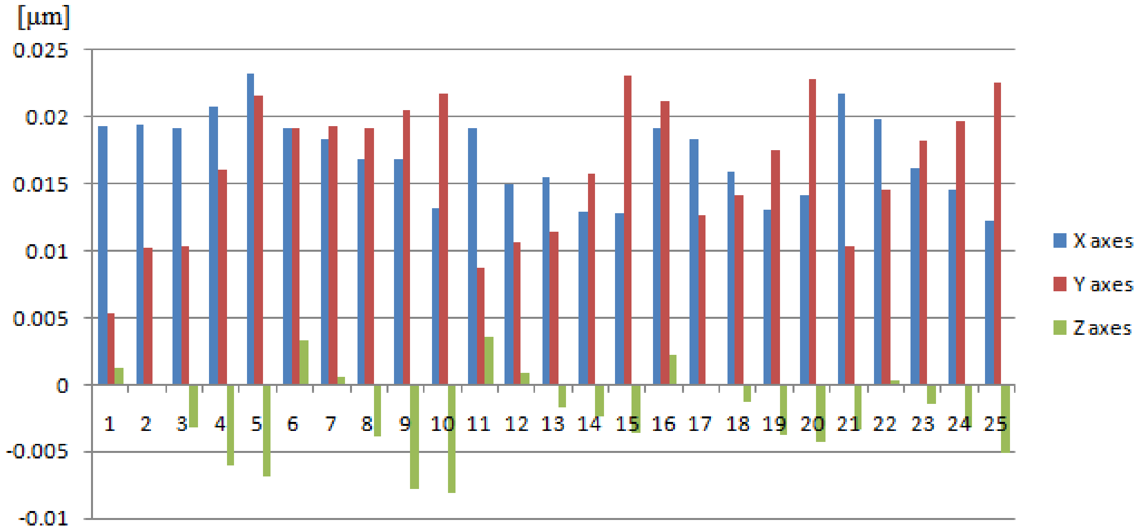

Fig. 4. Compensation values of *X*, *Y* and *Z* axes in the 25 points of the calibre

Figure 4 shows the evolutions of the compensation values on the three axes (X, Y and Z) in function of the position of the 25 points distributed inside the travel of each axis. This diagram in Figure 4 represents a portion only, i.e. 20% of the machine working space. The continuation of exploring the entire working space implies resuming the measurements after lifting the calibre by steps of 100 mm, through the four sets of supports (legs). In this manner the entire working space of the machine will be scanned and, afterwards, the corrections will be applied for each one of the 125 points of the working space.

5. CONCLUSIONS

The method being presented in this work assures an enhancement of the positioning accuracy on the entire working space of a CNC machine tool. It implies low costs and applies easily. The positioning accuracy may also be enhanced by increasing the number of measuring points. The method itself brings corrections both to the machine geometry and to the accuracy of the servo-control systems of the machine numerically controlled axes. In the first usage of a CNC machine tool the method may be successfully applied, just when the machine is a new one, because each and every measurement of the machine geometry has admissible values with cumulated influences on the positioning accuracy. This method may also be applied, in a relatively short time, anytime when suspicions come up on the tolerance deviations of the work pieces being machined. The history of the positioning accuracy measurements by using the method being presented, assures the possibility for comparing the results that is sufficient for analyses of the evolution of the wear and accuracy conditions of the CNC machine tool.

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