Influence of the positioning accuracy given by the positioning encoder of the CNC machine tools

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Abstract: The CNC machine tools are present at a large extent worldwide, for machining by cutting all kinds of work pieces. Their machining accuracy and quality are crucial to obtaining very accurate and intricate work pieces. The accuracy of a CNC machine tool is given by the quality of each and every kinematic linkage/coupling in its structure. This work aims at researching the influence of several constructive and functional factors on the positioning accuracy of a kinematic coupling in the structure of a CNC machine tool. The influence caused by noncompliance with the Abbé principle on the positioning accuracy of a feed kinematical linkage is analysed into detail, both at idle and load running. Out of this research useful conclusions are resulting for the CNC machine tool designers and builders, with respect to optimising several constructive factors, such as the location of the position encoder, location of the ball screw, stiffness of the directional guideways etc., in order to improve the accuracy of the CNC machine tool. The results of the theoretical research have been validated through experimental trials, confirming the impossibility of full compliance with the Abbé on the CNC machine tools.

1. Introduction
Generally, all machine tools include to their structure several kinematic couplings, linear and rotary, that provide the movements needed by the cutting tools for performing the machining process [1]. Each kinematic coupling that in most of the cases belongs to the fifth class has its guiding assured in two plans: one is providing the directing and the other one is providing the carrying support. The propulsion force of the kinematic coupling is located, in relation to the two guideways (directing and carrying), at positions possible in constructive terms, considering the vicinity of the constitutive elements. The kinematic coupling that is materialised through the moving element is also submitted to other forces, such as friction and requirements resulting from the cutting processes. All these forces lead to consequences on the elastic deformations [2]. The sensible element of the kinematic couplings, in terms of stiffness, is the guiding system that needs to provide a very low friction coefficient as well [3]. The consequences of the coupling being submitted to the forces mentioned above make the moving element to modify its position so that, upon the motion to a direction, a light swing of the moving element occurs, and, upon the motion to the reverse direction, case when the force senses are changed, the same light swing occurs, but in the reverse sense. During the linear motion of the moving element [4] the value of the “light swing” is variable, since it depends on the variation of the guiding system stiffness in relation to the kinematic coupling travel. As such, the group of forces that act on the kinematic coupling and is reified through a resulting force located at a certain distance from the
directing guideway axis (in one plane) and a certain distance from the carrying guideway axis (in the other plane), will generate a swinging torque in each plane. In consequence, there will be two light swings, in perpendicular planes, of the moving element during the linear motion of the kinematic coupling.

2. Abbé principle on CNC machine tools
The Abbé principle was first described by Ernst Abbé in the domain of metrology and it states: A measuring instrument must have the measuring direction coaxial (in line) with the measurer, as shown at figure 1.

The Abbé error occurs when a distance exists, named Abbé offset, between the measuring scale (measurer) and the axis to be measured that is caused by the angular error of the moving element. In case of the CNC machine tools the Abbé principle can be analysed in a similar manner, because a machine tool has several controlled axes, consisting of moving elements and whose motion is automatically measured by the position encoder. The location of the position encoder and the angular error of each moving element are important factors that influence the positioning accuracy and the machining accuracy of the machine tool, respectively. However, the analysis and compliance with the Abbé principle on the CNC machine tools is a complex problem because constructive and contextual aspects come up that are limiting the possibility of a full compliance with this principle. The aspects that take part to the analysis of the Abbé errors on CNC machine tools are:

a) On the controlled axes of the CNC machine tools indirect measurement is used for the position, especially in case of short and middle travels. In this case the position encoder is located on an intermediary element of the transmission system. In this case, for the analysis of the Abbé principle the measurer axis is considered the axis of the ball screw or rack (when the rack and pinion system is used).

b) The system of forces that act on the moving element of each controlled axis is variable and depends on the cutting process. In this case the Abbé error will be variable and, by default, the positioning accuracy will be variable too. The analysis of the Abbé principle on CNC machine tools and especially for finding the minimisation means of the errors requires two variants: the idle running and load running. This split into two variants is justified by the fact that in case of most of the CNC middle and large size machine tools the controlled axes first perform the positioning at idle running, then the moving element is clamped and afterwards the running process at load will begin. If the CNC machine tool is cutting through interpolation where more controlled axes participate and the cutting forces are differently directed spatially, the need of the analysis at load of the Abbé principle comes up. Moreover, the cutting forces that require the moving element are variable, depending on the parameters of the cutting duty.

c) A guiding system of a moving element of a feed kinematic linkage on CNC machine tools provides the linear guiding (coupling of the fifth class) in two planes: a directing one and a carrying one which is perpendicular to the first. The controlled axes in the architecture of a CNC machine tool
are oriented prominently horizontally, but at least one should be vertical. In case of the controlled axes whose moving elements are moving horizontally only the angular error in the directing plane will be considered, because the weight of the moving element will annul the angular error in the other plane. On the moving elements of the CNC machine tool that move vertically the angular error will occur in both planes because the weight of the moving element is annulled through balancing. In this case the Abbé error of the moving element in one plane will be found in the positioning accuracy of the controlled axis that includes the moving element and the Abbé error in the other plane will affect the accuracy along a direction perpendicular to the first. This Abbé error in the second plan is caused by the angular error in the first plane. The moving element subject to swing has no position encoder on this direction, since the machine tool has another controlled axis along it.

3. Ways to improving the positioning accuracy based on the Abbé error analysis

The way to find solutions to improve the positioning accuracy related to the Abbé error at a feed kinematic linkage of a CNC machine tool is represented in figure 2. The moving element 1 (the slide) moves horizontally along the guideways 2. The analysis is done at idle running. The direction guiding of the slide is performed through the surfaces 3 along which the rolling elements 4 are moving. The force $F$ necessary to drive the moving element 1 is developed by the ball screw 5, located at the distance $i$ from the symmetry axis of the directing guideways. The resisting forces consist of the friction forces $F_{f1}$ and $F_{f2}$ on the guideways and the swing moment $M_i$ of the moving element is:

$$M_i = F \cdot i - F_{f2} \frac{l}{2} + F_{f1} \frac{l}{2}$$  \hspace{1cm} (1)

The symbols mean: $l$ – distance between the surfaces that provide direction guiding; $L$- slide length.

The presence of the swing torque $M_i$ leads to a light swing of the moving element by the angle $\alpha$ and eventually is concretised upon the tool-work piece contact point into the errors $e_x$ and $e_y$, as per figure 3. The relations that establish the values of the two errors $e_x$ and $e_y$ are obtained from the geometrical analysis of figure 3:

$$e_x = \alpha \frac{[\sin B - \sin(B-\alpha)]}{\cos B}$$  \hspace{1cm} (2)

$$e_y = \alpha \frac{[\cos(B-\alpha) - \cos B]}{\cos B}$$  \hspace{1cm} (3)
\( B \) is the angle between the vertical axis (\( a \)) that passes through the swing centre of the directing guideways and the axis that passes through the tip of the cutting tool. The swing torque \( M_i \) at idle run can be annulled through the suitable location (distance \( i \)) of the ball screw.

\[
0 = F \cdot i - \frac{F_{f1} l}{2} \cdot \frac{F_{f2} l}{2} \tag{4}
\]

\[
i = \frac{(F_{f1} F_{f2}) l}{F} \tag{5}
\]

\( F_{f1} \) and \( F_{f2} \) are the friction forces shown at figure 2. If \((F_{f1} - F_{f2}) \neq 0\), the location of the ball screw will be displaced from the axis of the directing guideways, so \( M_i \neq 0 \) will not happen. The analysis presented above will be sustained if the position measurement is direct, having the position encoder in line with the symmetry axis of the directing guideways. If the position encoder is located just in line with the tool-work piece contact point, the error \( e_c \) is compensated, so it’s only the \( e_y \) error that remains. The location of the position encoder is important with respect to lowering the Abbé error, but constructive issues are limiting the possibility of compliance with this rule. If the measurement of the slide position is indirect, an analogy could be done with the direct measurement by considering that the position encoder is in line with the ball screw. It is to be noticed that the light swing of the slide, reified through the angle \( \pm\alpha \), is variable in relation to the travel. This issue is mainly caused by the parallelism deviation of the directing guideways surfaces. In case when the moving element performs the positioning at load, the analysis presented above will be subject to changes. On the moving element the cutting force \( F_a \) will be also acting, situation that requires an increase of the driving force \( F \). From the analyses on a slide of a CNC machine tool presented above, analyses performed both at idle running and load running, the following conclusions will result concerning the improvement of the positioning accuracy in relation to noncompliance with the Abbé principle:

1) The need for increasing the stiffness of the directing guideways of all controlled axes, both horizontal and vertical, by using elements that provide preloading. An optimal determining of the preloading value in case of the rolling elements provides a stiffness increase by approximately 45%. As rolling elements, the rolling packs with one or more circuits are recommended, instead of the usage of balls. For the large size machine tools that are fitted with hydrostatic lifting the optimisation of the hydrostatic elements (pockets) is recommended with a view to increase stiffness. If a CNC machine tool has three controlled axes, two of them (\( X \) and \( Y \)) will have a horizontal motion and the third one (\( Z \) axis) will move vertically. Because of the noncompliance with the Abbé principle on \( X \) axis, the errors \( e_x \) and \( e_y \) will be present, on \( Y \) axis there will be \( e_y \) and \( e_x \) and on \( Z \) axis the Abbé errors in the two planes (directing and carrying) will be considered, i.e. \( e_z \), \( e_x \), \( e_y \) as well. The \( Z \) axis with vertical motion having a balanced weight of the moving element should feature a high stiffness in both planes. Consequently, the use of preloading of the moving element guideways becomes essential, especially because the distance from the guideways to the tip of the tool is relatively long as it is imposed by constructive reasons, needed to provide the tool penetration beyond the table centre.

2) The need for minimising the swing torque of the moving element in the directing plan for the axes with horizontal motion. For the axes with vertical motion both planes (directing and carrying) are considered. For this purpose, it is recommended the resisting forces, materialised at idle running through the friction forces in the guideways, to be as low as possible; usually it is recommended the use of rolling guideways or guideways with liquid friction. For lowering the swing torque of the moving element it is also necessary the force arms to be as short as possible or, if possible, even zero. For this reason the location of the ball screw in relation to the symmetry axis of the directing guideways is very important. It is desirable, if there are location constructive possibilities, the application point of the slide driving force to coincide with the resisting force and with the symmetry axis of the directing guideway, situation when the swing torque will be zero at idle running and the Abbé errors will become null.
3) Another way to decrease the swing angle $\alpha$ consists of increasing the length $L$ of the moving element, but with a compromise, materialised in shortening its travel. There is the possibility for keeping the travel of the moving element but, in this case, the length of the guideways will increase and, by default, the machine overall dimensions and price eventually.

4) The location of the position encoder as close as possible to the measuring line, if possible even to coincide. The measuring line of the moving element is very different, even specific for each and every axis in the structure of a CNC machine tool. Moreover, the measuring line varies from an operation to another during the usage of the machine. If the contact between the work piece and the tool modifies during cutting, the measuring directions along the three axes ($X$, $Y$ and $Z$) will modify, as well. In case when the cutting forces are null, i.e. the machine runs idly, the measuring direction of each axis is established by the location points of the calibrated measuring system for determining the positioning accuracy (VDI/DGQ 3441). Consequently, the location of the position encoder of the moving element should coincide to the measuring line, reified by the calibrated measuring system (laser interferometer or scaled microscope). The compliance with this rule, if possible in constructive terms, will provide an improvement of the positioning accuracy because the Abbé error is inside the position adjusting loop. There are situations when this rule cannot be followed, but the designer can consider it for minimising the negative effects.

4. Experimental trials

The machining centre CV belonging to the University “Vasile Alecsandri” in Bucău is the CNC machine tool on which the experimental trails have been performed. The machine has three controlled axes ($X$, $Y$ and $Z$) and the following travels: $X = 700$ mm, $Y = 600$ mm and $Z = 500$ mm. The position measuring system is direct, fitted with linear position encoders located between the guideways of each axis. Trials have been performed on the axes with horizontal motion ($X$ and $Y$) through the measurement of the positioning accuracy by means of a laser interferometer placed at two positions, having two values of the Abbé offset. One of the positions made the axis of the laser interferometer to coincide with the axis of the position encoder, whilst the other one has the interferometer axis located on the median zone of the moving element that is also the location stipulated by the standard VDI/DGQ 3441 for determining the positioning accuracy. For determining the positioning accuracy ($p$) the algorithm for statistical determining and processing stipulated by the standard VDI/DGQ 3441 has been applied. The results of the trials are shown at figure 4 for $X$ axis and figure 5 for $Y$ axis.

![Figure 4. Positioning accuracy ($P$) of $X$ axis.](image1)

![Figure 5. Positioning accuracy ($P$) of $Y$ axis.](image2)

The diagram I represents the positioning accuracy when the interferometer is located in line with the position encoder, where the errors are low ($\pm2.5$ μm) and the diagram II corresponds to the interferometer located on the middle of the machine table. In the case of diagram II there is an increase of the positioning error, but a quasi-constant variation between the two diagrams may be noticed. This aspect is correlated with the cause of error generation, i.e. the presence of the swing angle and distancing of the position encoder from the measurement line. The systematic characteristic of the
positioning errors on the two axes $X$ and $Y$ at idle running allows the insertion of corrections along each axis, i.e. for $X$ axis the $e_x$ component only, without the component $e_y$. The correction values are input to those 1000 points, for each sense, mentioned in the offer of each numerical control.

5. Conclusions

From the analysis of the structure of a feed kinematic linkage of a CNC machine tool it results that an important role is held by the location of the position encoder in relation to the directing guideways of the slide, beside other conditions that depend on the stiffness of the guiding system, type of the measuring system (direct or indirect) and diminution of the swing torque. Because the requirement conditions of a slide on a controlled axis of the machine are variable, less in case of idle running, the application of the Abbé principle is impossible to be achieved. Just a small part of the errors, the ones at idle running and, in this case, one component only of the error that is systematic, allows the input of corrections for improving the positioning accuracy. The following recommendations may be given to the machine tool builders: - the location of the ball screw in relation to the directing guideways and the resultant of the slide resisting force is very important; - the correct choice of position encoder location in relation to the measuring direction; - use of guideways with proper stiffness and low friction coefficient; - use of additional means for minimising the slide swing upon the change of the motion sense.

6. References

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