Improvement of machine tool accuracy through ball screw location optimisation in relation to the guideways of the axes

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Abstract: An important role in obtaining a high positioning accuracy is also played by the location of the ball screw in relation to the guideways of each axis. This makes that noncompliance with the Abbé principle to lead to higher positioning deviations. The compliance with the Abbé principle is difficult to be achieved from the constructive point of view because the cutting forces differ in terms of direction, sense and value within the working space of the machine tool. This work develops a mathematical model that allows finding the location direction of the ball screw in relation to the guideways, so that the positioning accuracy is increased. The conditions that may influence the improvement of the positioning accuracy by increasing the guideway stiffness and settling the dimensions of the moving element are studied in this work, as well. The mode of locating the position encoder in case of direct measurement that, together with the noncompliance of the Abbé principle leads to affecting the positioning accuracy is also presented. The results have been obtained experimentally on a milling machine where the ball screws have been located symmetrically in relation to the main guideway.

1. Introduction
The systems of transmission and transformation of the rotation motion from the servomotor to the moving element prominently used in the manufacture of the CNC machine tool translation axes are of ball screw –nut or rack and pinion types. The most used are the ball screw – nut systems that confer a low friction coefficient and high efficiency (η=95-98%) as well [1]. Besides the high efficiency and low friction coefficient provided by the ball screw – nut systems, a high accuracy is assured as well, under the conditions when the construction of the mechatronic system includes a measuring system of direct type, with a loop type feedback [2,3]. Besides the motion transmission system, a particular importance has the guiding system of the moving element composed of guideways with sliding or rolling elements. The motion of the moving element along the guideways has to be performed with a proper linearity in order to provide precise positioning both in the absence of the outer cutting forces and in their presence. In this case, an important role for obtaining high positioning accuracy is played by the location of the ball screw in relation to the guideways of the programmable kinematical axis, because at the change of the motion directions of the moving element a swinging moment will occur on the direction of the slide motion, generated by the different resultants of the resistant force and the driving force. This swing in the horizontal plane will negatively influence the positioning accuracy, through noncompliance with the Abbé principle [4,5]. Undesirable effects will also be recorded in case of the tipping of the moving element where, the noncompliance with the Abbé principle will lead to measuring errors [6].
2. Block diagram and functioning of the feed kinematical linkage

The structure of the CNC machine tools includes various programmable feed kinematical linkages. Each programmable axis of a CNC machine tool is driven by an A.C. motor with variable rpm. Figure 1 shows the block structure of a programmed axis with the response loops for speed \( Bv \) and position \( Bp \), having as means of transformation and reduction the ball screw mechanism.

![Figure 1. Block diagram of the feed kinematical linkage with the speed and position loops.](image)

Within the speed canned loop \( Bv \), the speed encoder 5 can provide the constant rpm of the A.C. motor 6 that could be compensated or corrected if errors come up, by means of the frequency converter 3. The signal will be amplified and transmitted to the A.C. motor until the error is annulled.

The position canned loop \( Bp \) of the position linear encoder provides a direct measurement, giving a positioning of high accuracy of the moving element 9, which moves along the ball screw 8. Through the input signal \( i \) (commanded or pre-set signal) the position encoder 10 will generate a response \( r \) that will be sent to the comparator block 2 in the CNC structure 1. In function of the measurement system (direct or indirect) used in the construction of the feed kinematical linkage of the CNC machine tools the swing of the moving element upon the change of the motion direction will negatively affect the positioning accuracy [3].

The feed kinematical linkages of the CNC machine tools are driven by motors on each controlled axis and the functioning principle of the axes is alike. The feed rates of the programmable axes of the machine are independent and feature the possibility for continuous adjustment in relation to the contour of the work piece. In order to obtain the desired contour of the machined surface, the interpolation block is necessary to exist into the machine control, it has the role to permanently correlate the rpm of the servomotors with the contour of the work piece being machined.

![Figure 2. Running diagram of the feed kinematical linkage as an assembly.](image)

Figure 2 shows the functioning scheme of the feed cinematic linkage in canned cycle. For the feed kinematical linkage to run it is necessary the imposed measure \( C \) and the feed rate \( S \) to be pre-set into the machine control that, after going out of the computer of the CNC machine will become the controlled speed \( Vc \). \( PE \) means the sampling period and is the time between the moments when the position loop gets closed. The position encoder will measure the speed and will send a response to the comparator of the machine control that will compare the controlled speed \( Vc \) and the measured speed \( Vm \), from their difference the instant position error \( Ei \) will be obtained. The total position error or the follow-up error \( Eu \) represents the sum of the instant errors \( Ei \), and the factor \( Ae \) represents the amplification of the command that will compensate the follow-up error. The digital signal is afterwards converted into analogue, \( D/A \) and sent to the frequency converter \( CF \).
Table 1. Crossing a measure of the feed kinematical linkage.

| PE  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Vc  | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0   | 0   | 0   | 0   |
| Vm  | 0   | 20  | 50  | 80  | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 60  | 40  | 25  | 15  |
| Ei  | 100 | 80  | 50  | 20  | 0   | 0   | 0   | 0   | 0   | 0   | -100| -60 | -40 | -25 | -15 | -10 |
| Eu  | 100 | 180 | 230 | 250 | 250 | 250 | 250 | 250 | 250 | 250 | 150 | 90  | 50  | 25  | 10  | 0   |
| Ei - Eu | 100 | 180 | 230 | 250 | 250 | 250 | 250 | 250 | 250 | 250 | 150 | 90  | 50  | 25  | 10  | 0   |

Table 1 and figure 3 are exemplifying the crossing of a measure of a feed kinematic linkage numerically controlled at the commanded speed $V_c = 100 \text{ mm/PE}$. The transient duty will end when the follow-up error $E_u = 0$. The closing of the position loop will be resumed at each sampling period PE. The acceleration/deceleration curves of the slide $S$ can be adjusted as necessary with the help of the frequency converter parameters, where the integrating part will be modified. However, in case of the advanced numerical controls, their structure includes separate blocks for acceleration and deceleration, so these will be programmed as necessary. From the functional analysis described above it may be noticed that the positioning accuracy of the slide $S$ is automatically assured, due to the position loop $B_p$. If swings of the slide $S$ occur upon the change of direction, the position loop will not be able to automatically compensate these errors that, of course, will affect the positioning accuracy.

3. Influence of ball screw location on the positioning accuracy

The location of the ball screw in relation to the directing/main guideway makes the driving force of the moving element not to coincide with the resistant force of the slide. In this case forces occur that generate a torsion moment that require the moving element by producing the slide swing in both directions, so that, upon the reversal of its motion, the forces change their directions. As a result of the slide swing the positioning accuracy is negatively influenced.

As shown at figure 4, the slide $S$ that has assured its directional guiding through the surfaces $I$ and $II$. On the slide the work piece $P$ is fixed that is submitted to cutting under a cutting force $F_{2S}$. 

![Figure 4. Location and distance of the forces in relation to the symmetry axis of the guideway.](image)
In this case, when the driving force $F_a$ of the moving element that is transmitted through the ball screw located at the distance $z$ from the symmetry axis of the guideway and the cutting force $F_{as}$ located at the distance $v$ from the same symmetry axis as well as considering the friction forces $\mu F$ in the guideways, the following equations (1) and (2) can be written:

$$F_{as}y + \mu F(x + q) - FL = 0$$

(1)

$$F_a = F_{as} + 2\mu F$$

(2)

After resolving the system of equations, the equation (3) will result for the driving force $F_a$:

$$F_a = F_{as}\left[1 + \frac{y}{(\frac{L}{2\mu} - z)}\right]$$

(3)

From the analysis of the equation (3) it may be noticed that in order to have a minimal swinging moment on the slide it will be necessary to decrease as much as possible the rate of the driving force $F_a$. This can be done in this case when the ratio $\frac{y}{(\frac{L}{2\mu} - z)} = 0$ and the driving force $F_a$ is equal to the cutting force $F_{as}$, ($F_a = F_{as}$). This is possible when $y = 0$. As such, $F_a$ and $F_{as}$ are coaxial. In practice, especially when contouring operations are performed, this thing is not always possible because the cutting force $F_{as}$ has various locations.

Another solution for obtaining a minimum value for the driving force $F_a$ or for to have $F_a = F_{as}$ is the case when $L = \infty$ or $\mu = 0$, that is practically impossible. Under these conditions only a decrease of the driving force $F_a$ can be obtained by increasing the ratio $\frac{L}{2\mu} - z$. In this case, for obtaining, however, a decrease of the rate of the driving force, it is sufficient the denominator $\frac{L}{2\mu} - z$ to be increased. The limit case will be when $z = 0$. This means that the driving force $F_a$ coincides with the symmetry axis of the guideway. Because the driving force $F_a$ of the moving element is transmitted through the ball screw, it is necessary the ball screw to be located in the median area of the guideways. Through this design solution, correlated to the stiffening of the guideways and location of the work piece as close as possible to the centre of the machine table, the driving force $F_a$ could be brought closer to the cutting force $F_{as}$, that will lead to decreasing the swinging moment of the moving element or, moreover, the swinging moment will become zero when $F_a$ and $F_{as}$ coincide.

The research presented in this work leads to the conclusion that the location of the ball screw in relation to the guideway that assures the directing of the moving element, allows the possibility to decrease the forces that cause the slide swinging and affect the positioning accuracy, respectively.

4. Steps for increasing the positioning accuracy

From the research being presented with respect to the location of the ball screw in relation to the directing guideway of the slide, it results that the location of the cutting force is variable, in function of the work pieces being machined and the swing motion of the slide upon the change of direction can be decreased. There are various possibilities to intervene in other ways - except for the location of the ball screw - that can reduce the influence of this phenomenon on the positioning accuracy; these will be presented below.

a) Location of the position encoder. When the measurement of the moving element is direct, the location of the linear position encoder is to be considered, because upon the change of direction, the measuring accuracy will be affected by noncompliance with the Abbé principle, because of the forces $\mu F$ that create the swinging moment, as per figure 5. The optimal location version of the position
encoder with the lowest influence on the positioning accuracy is that one where the encoder is located in the median area of the guideway and the value of the slide swinging angle $\alpha$ is much decreased.

Figure 5. Methods of location of the linear position encoder.

In order to obtain a high positioning accuracy when the position encoder is located at one of the sides of the moving element, it is necessary the guiding system to be designed with an increased stiffness and the direction of the driving force $F_{d}$ to be as close as possible to or coaxial with the direction of the cutting force $F_{c}$. In case of the indirect measurement, the rotary position encoder may be located on the intermediary elements of the feed kinematical linkage. In order to decrease and keep under control the positioning errors when the measurement is indirect, the portion of kinematical linkage from the encoder to the moving element has to be manufactured at a superior accuracy class. When the position encoder (indirect measurement) is located at one of the ball screw ends, different values of the positioning measure will be recorded, in function of the ball screw end. If the encoder is located at the opposite end of the driving servomotor, the error will be lower, because the position loop will also include the angular deformation of the ball screw that could be compensated through the position loop.

b) Increasing the stiffness of the directing/main guideway. The stiffness of the directing guideway has a major importance for obtaining a good positioning accuracy. In order to decrease the swing of the moving element, the directing guideway will be designed with rolling elements such rollers or roller packs that can carry high preloading forces. These confer a high stiffness and eventually a positioning of high accuracy to the moving element. The preloading force applied to the directing guideway in horizontal plan is recommended to be 2, 3 of the total value of the driving force that requires the roller pack. In consequence, it is necessary the directing guideway stiffness to be provided with elements for adjusting the preloading of the rolling elements.

c) Electronic compensations of the swinging motion effects. In this case at the final part of calibration of the positioning accuracy correction values that are offered by the CNC equipment can be input. The new numerical controls offer more than 1000 correction points on the entire travel of the axis that will be automatically taken over upon the change of direction. These correction values help with increasing the positioning accuracy. The CNC equipment offers as well, upon the programmer’s request, the possibility of positioning from one direction, thus decreasing the swing effects of the slide upon the change of direction.

d) Decreasing the influence of the moving element swing through the Gantry function. When the distance between guideways is large, the swinging in horizontal plan upon the direction change is increased. In order to avoid this inconvenient that affects the positioning accuracy, the usage of a double type kinematical linkage is imposed that is driven in parallel by two separate servomotors. This system has a permanent electronic connection between the two kinematical linkages through the Gantry function of the numerical control of the machine. Each kinematical linkage has its own position loop and speed loop and these are electronically connected such as to have the possibility to get synchronised while following a trajectory or when the motion direction is being changed, in order to avoid the swinging of the moving element in horizontal plane. The Gantry function requires an axis to be the driving axis and the other one to be the idle axis and, through the permanent connection of the measuring systems, the values measured by encoders will be compensated; afterwards an additional signal will be generated for the idle axis such as to compensate the difference of position between the two kinematical linkages.
Through the synchronisation of the axes the perpendicular position of the moving element to the motion direction will be maintained, inclusive of the change of the motion direction.

5. Experimental results
The trials have been performed on a test stand that materialises a feed kinematical linkage, belonging to the Mechatronic Laboratory of Bacau University. The travel of the moving element is 600 mm, the resistant force is 400 daN, located at 50 mm distance from the axis of symmetry of the guideway. Tests have been carried out in the versions with indirect measurement – curves $a$ and $b$ and direct measurement – curves $c$ and $d$. The results are shown at figure 6.

![Figure 6. Position error of the moving element.](image)

The curves $a$ and $c$ show the error of the position $E_P$ during the slide motion along one direction and the curves $b$ and $d$ along the opposite direction. The results show the return backlash $J_i$ at the indirect measurement caused by the slide swing at the direction change and the position error is increasing because of the cumulated error of the ball screw pitch that is not compensated by the position loop. In case of the direct measurement the value of the return backlash $J_i$ is lower and the value of the position error $E_P$ in relation to the travel is lower, i.e. approximately 0.009 mm.

6. Conclusions
From the researches it results that the slide swing is present upon the direction change and, in function of its extent, correction steps need to be applied. The choice of the correction method is dictated by the machine purpose and by the costs being involved. Even from the stage of the machine conception the choice of a directing guideway of high stiffness is imposed, as well as the location of the position encoder at a position that minimises the influence of the return backlash on the positioning accuracy and, afterwards, the input of the correction parameters. During the conception stage as well, the driving version has to be chosen, whether with one or two (Gantry) kinematical linkages and the type of the position measuring system (direct or indirect).

7. References
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