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CIRCULAR PATH FOR CNC MACHINE TOOLS

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Abstract: *Machine tools are built from many components and each component contributes motion error to the final tool tip position. There are multiple error origins including geometric, static and dynamic loading, thermal, mismatching between servo-loop parameters, interpolation etc. In the same time, the control of machine tools affects the accuracy of the work-piece. Therefore, in order to achieve high performances of feed drive system is required to analyses simultaneously both mechanical and control systems. To achieve high quality and productivity during continuous contouring, it is important to know how two axes work together. For this reason, to investigate the influence of the interactions on the system performance, circular tests are conducted. Results of the process make it possible to understand accurate dynamic behavior of a feed drive system.*

Key words: *feed drive system, contour errors, trajectory measurement, position control loop.*

1. INTRODUCTION

Accuracy could be defined as the degree of agreement or conformance of a finished part with the required dimensional and geometrical accuracy. Error, on the other hand, can be understood as any deviation in the position of the cutting edge from the theoretically required value to produce a workpiece of the specified tolerance. The extent of error in a machine gives a measure of its accuracy; that is the maximum translation error between any two points in the work volume of the machine. This, of course, depends on the resolution of the system. Positioning can never be more accurate than this as there will be no further feedback to improve the positioning within this range (typically of the order of 1 μm). However, more important then system resolution, are the errors that occur between the measurement point and the feedback point [1].

Errors occur at the circular contour and on all curved paths. These errors depend on the type of measuring system and they have different effects. The machining of a circular contour involves two feed axes. Their position set points are computed by interpolator of the CNC according to the selected type of interpolation, and applied to the feed drives. In addition to the interpolation, a great number of parameters and disturbance variables are very important to the dimensional accuracy of the actual contouring path, some of which will be analyzed in this paper.

Error measurement is not only made for error compensation of a measuring (CMM) or machine tools, but also to discover problems in the design, in the development stage, for readjustment and reworking in the manufacturing stage. The methods and the devices for measuring motion accuracy of NC machine tools are presented here.

To achieve the high precision and super-finishes, static positioning accuracy or repeatability is not enough. The acceptable contour will depend on several factors including cutter path complexity, machine static and dynamic accuracy, the machine acceleration and deceleration rate, the machine control system and compensation, data processing rate, etc.

Any dynamic characteristics in the machine tools will lead to the generation of vibrations, the effects of which can lead to poor surface finish on the work piece increased machine tool wear, as well as tool fracture and damage to both the work piece and machine. Under continuous machining conditions, two types of vibrations occur because of movement between work piece and tool. These are externally excited and self-excited vibrations. All these errors in the machine tools interact with each other and make a complex situation for error compensation research.

2. AN OVERVIEW OF MACHINE TOOLS ERRORS

The motion error sources in NC machine tools are due to mechanical structures and due to servo control systems [2].

Motion errors due to mechanical structures:

- errors in positioning mechanism (uniform expansion or contraction of the ball screw and linear scale, cyclic error of the ball screw and linear scale, noise in detectors, backlash);
- profile errors of guide way (squareness errors between two axes, straightness errors, rotational moment, parallelism error, friction of the sliding cover);

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- errors that can be compensated by servo control system (lost motion, stick motion, stick slip, misting of pitch error compensation).

  Motion errors due to servo control systems:
- mismatching of position loop gains;
- radius reduction in circular interpolation due to response lag;
- response lag or overshoot at junctions of two interpolation lines.

2. CIRCULAR CONTOUR ERRORS BY THE INTERACTION OF FEED AXES

A typical example for errors dependent on acceleration and velocity can be recorded in a circular interpolation test on a vertical-machining center. Heidenhain Company, the producer of rotary and linear encoders, made this test. The results are: where position control is by rotary encoder and ball screw, the circles traversed at higher velocity deviate significantly from the ideal path [3]. The same machining center shows significantly better contour accuracy when is equipped with linear encoders (Fig. 1).

There are two types of contouring errors: errors on the circular contour, which are depending from the contouring rate and the circle radius; distortions of the circular contour, which result, when the participating axes do not responding equally.

Depending on the location at the machine tool where the measured data acquisition takes place, we differentiate between direct and indirect position measurements. Depending on the location at the machine tool where the measurement acquisition takes place, we differentiate between direct and indirect position measurement [4]. Figure 2 illustrates the indirect and direct position measurement in the position control loop for a lead screw drive. Where: w_x – is the position command variable; Δx – the position control deviation; v_i – the actual velocity value; v_s – velocity set point value; r_x – the position feedback variable. For rotary as well as linear drives, where the actual speed value is obtained from the position measurement, the actual value encoder must be installed free of backlash and tilt.

At a circular motion with an angular frequency ω equal to the angular velocity v_B / r_i, the actual position values of the two feed drives have the following time characteristic:

$$x_i = \hat{x}_i \sin(\omega t)\,;\;\; y_i = \hat{y}_i \cos(\omega t + \Delta\varphi) \qquad (1)$$

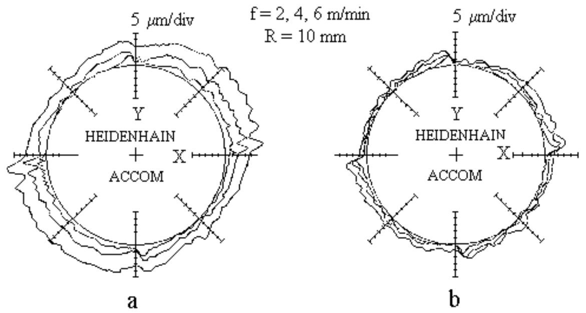


Fig. 1. Circular test of machining center a) position control with rotary encoder; b) position control with linear encoder.

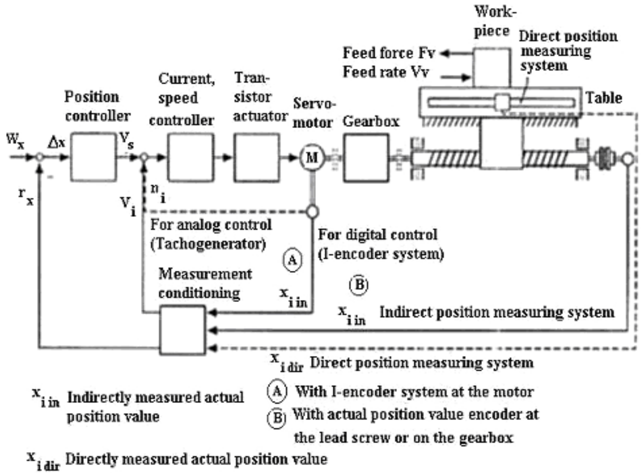


Fig. 2. Indirect and direct position measurement in the position control loop [5].

The actual radius of the circle is $r_{i0} = \hat{x}_i = \hat{y}_i$, and the phase shift angle difference between these axes is $\Delta\varphi = 0$. The result would be a distortion-free circular contour.

If the axes X and Y have different command responses, then $\hat{x}_i \neq \hat{y}_i$; $\varphi_X \neq \varphi_Y$, and we obtain different absolute values from the amplitude responses, and a phase shift angle difference $\Delta\varphi$ from the phase responses. Both differences result in a distortion of the circular contour.

2.1. Amplitude errors

The resulting circular contour is calculated from the geometrical sum of the actual positions of both axes. If $\hat{x}_i \neq \hat{y}_i$, but $\Delta\varphi = 0$, the actual contour will be staved in elliptically, in the direction of the axis with the smaller amplitude ratio. The instantaneous radius value is the result of the following correlation:

$$r_i = \sqrt{\hat{x}_i^2 \sin^2(\omega t) + \hat{y}_i^2 \cos^2(\omega t)}\,. \qquad (2)$$

The largest circular contour deviation occurs at the point where one of the feed axes reaches its maximum value. Calculating this deviation caused by the different command responses of the two-position control loops of the X and Y axis from the difference of the two actual values

$$\left|\Delta r_{FwL}\right| = r_s \left\| F_{wLX} \right| - \left| F_{wLY} \right\|. \qquad (3)$$

Figure 3 shows a contour where the Y axis have a smaller amplitude ratio than the X axis. The circle is staved in the direction of Y. Not are drawn the errors caused by the contouring rate and a possibly existing distortion caused by the mechanical system, which additionally occurs in the case of the indirect measuring system.

In the case of the *indirect measuring system*, we might have the distortion caused by the position control loops and errors caused by different mechanical transfer elements.

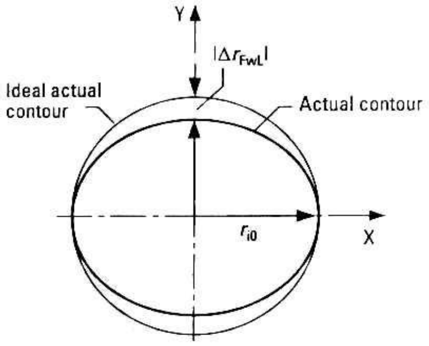


Fig. 3. Circular contour distortions due to amplitude errors.

$$\left|\Delta r_{Fmech}\right| = r_s \left\|F_{mechX}\right| - \left|F_{mechY}\right\| . \tag{4}$$

For the position control loops and the mechanical transfer elements together we obtain a distortion error

$$\left|\Delta r_F\right| = r_s \left\|F_{wLX}\right| \cdot \left|F_{mechX}\right| - \left|F_{wLY}\right| \cdot \left|F_{mechY}\right\| . \tag{5}$$

The absolute value of the radial error is indicated, since the actual contour can be larger or smaller than the distortion free contour. The error components of the position control loops and the mechanical system can compensate each other.

For the indirect position measuring system, the approximate total distortion error is

$$\left|\Delta r_F\right| \approx \left|\Delta r_{Fmech}\right| - \left|\Delta r_{FwL}\right| . \tag{6}$$

For the *direct measuring system* a breakdown into a position control loop component and a mechanical component is not possible. The generated distortion error caused by unequal K_V factors, unequal delay times $T_{\sigma x}$ and/or unequal mechanical natural frequencies $\omega_{d\min}$ is calculated with equation (3).

2.2. Phase error

In order to determine the distortions caused by different phase responses, we can set $\hat{x}_i = \hat{y}_i = r_{i0}$, and we have

$$r_i = r_{i0}\sqrt{\sin^2(\omega t) + \cos^2(\omega t + \Delta\varphi)} . \tag{7}$$

The actual radius at the angles $\omega t = (1/8)2\pi$ and $\omega t = (3/8)2\pi$, i.e. the 45^0 points between the feed axes, we have

Minimum at $\omega t = \dfrac{1}{8}2\pi;\ r_i = r_{i0}\sqrt{1 - 0.5\sin(2\Delta\varphi)}$,

Maximum at $\omega t = \dfrac{3}{8}2\pi;\ r_i = r_{i0}\sqrt{1 + 0.5\sin(2\Delta\varphi)}$.

We obtain an expansion or a contraction of the circular contour at the 45^0 points, depending on the difference between the two-phase shift angles. Figure 4 shows a schematic view of the contour distortion caused by phase error.

The phase shift angle of the two axes for the position control loops and for the *direct measuring system* is:

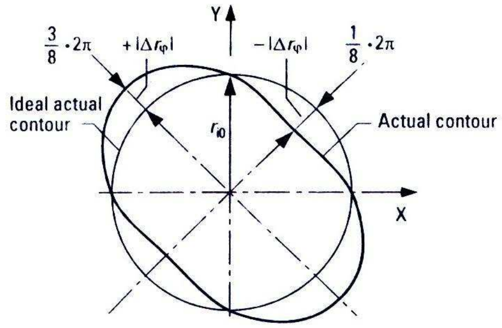


Fig. 4. Circular contour distortions due to phase error.

$$\Delta\varphi = \left|\varphi_{wLX} - \varphi_{wLY}\right| . \tag{8}$$

The phase shift angles of the two axes for the mechanical transfer elements is

$$\Delta\varphi = \left|\varphi_{mechX} - \varphi_{mechY}\right| . \tag{9}$$

The phase shift angles of the two axes for the position control loops including mechanical transfer elements and the *indirect measuring system*

$$\Delta\varphi = \left|(\varphi_{wLX} + \varphi_{mechX}) - (\varphi_{wLY} + \varphi_{mechY})\right| . \tag{10}$$

The distortion error caused by different phase shift angles in the position control loops and/or the mechanical transfer elements are calculated with relation

$$\left|\Delta r_\varphi\right| = r_{i0}\left(\sqrt{1 \pm 0.5\sin(2\Delta\varphi)} - 1\right). \tag{11}$$

Since the ideal actual radius in conventional machining is approximately equal to the set point radius, we set $r_{i0} \approx r_s$ and obtain:

$$\left|\Delta r_\varphi\right| \approx r_s\left(\sqrt{1 \pm 0.5\sin(2\Delta\varphi)} - 1\right). \tag{12}$$

The radius distortion at the circle is indicated as an absolute value. The phase error results due to the two signs under the root in a $\pm$ value. The circle will expand and contract. The K_V factor and the lowest mechanical natural angular frequency $\omega_{d\min}$ also affect any errors at the circle caused by the distortion of the ideal contour due to differences in the two axes participating to the interpolation. Both values must be as high as possible in order to keep the errors small [6].

In conclusion, we can say that:

- Errors and distortions occur at the circular contour and on all curved paths depending on the type of measuring system they have different effects;
- • In addition to the contouring rate dependent errors, unequal parameters and variables in the axes involved in the motion also generate distortions of the contour path. These are separated into amplitude and phase errors.
- Amplitude errors cause a contraction of the circle in the direction of the axes with the smaller amplitude ratio.

- Phase errors cause an expansion and a constriction in the 45^0 diagonals between the feed axes directions. The phase error is a $\pm$ value;
- Both errors usually occur combined, so that the cause for the distortion cannot be clearly determined with a circular contour test.

3. CONTOURING ERRORS MEASUREMENT

Circular tests provide a quick and efficient way to measure the machine's contouring accuracy and then to diagnose its error sources. Circular tests are accepted in ISO 230-4 [7].

The diagnosis methodology to identify motion error source in NC machine tools based on the double ball bar (DBB) method is now widely accepted in today's industry. Typical DBB devices consist of two high-precision balls connected by a telescoping bar, and the distance between two balls is measured by a linear scale installed on the telescoping bar. The DBB device is used to measure a contouring error profile as the machine is traversing along a circular trajectory (Fig. 5).

Today's market requires a motion accuracy test under the condition where the DBB test cannot be performed. For example, most DBB systems work with radii of 50 ~ 300 mm, although some applications require the machine to perform a circular interpolation of smaller radius. Furthermore, the measurement accuracy of the DBB method is impaired at the feed rate higher than 10 m/min, due to the friction between the ball and the magnetic socket. Another critical disadvantage of the DBB method is that it is restricted only to circular tests due to its nature [8 and 9].

Cross grid encoder method, or the KGM method development by Heidenhain is used for the measurement of two-dimensional contouring error. Most importantly, there are no restrictions on the motion to be measured due to a mechanical linkage, as in the DBB method. Since the KGM method is non-contact optical measurement, it is more suitable for high-speed and high-accuracy measurement [3].

The KGM method observes the relative error between a spindle (tool tip) and a table (work-piece). Its contouring error profiles contain not only motion errors due to CNC servo systems, but also those due to errors in mechanical structures of the machine. On the other hand, contouring error profiles of position feedback signal do not contain motion errors due to mechanical errors. Therefore, by comparing these two profiles, one can distinguish motion errors due to servo control systems from those due to mechanical structures. Many latest NC machine tools have a fast CPU and high-capacity memory, which makes it easy to sample position feedback signal in a fast rate. The sampling of position feedback signal requires no additional physical device if the NC machine tool has an additional memory to store sampled data.

The resolution of the grid encoder is 4 nm in its two directions; the resolution of the three linear displacement transducers is 20 nm. The resolution for the rotations depends on the distances between the optical heads and the linear displacement transducers.

The diagnosis methodology based on the DBB measurement mainly focuses on motion errors due to mechanical structures. The diagnosis method based on KGM focuses more on motion errors due to CNC servo control systems. Compared to motion errors due to mechanical structures, those due to CNC servo control systems are easier to compensate by properly re-tuning parameters in servo controllers. After the measurement and diagnosis of contouring errors, this method automatically tunes servo parameters in order to reduce contouring errors.

4. EXPERIMENTAL SET UP

Three axes milling machine is used for the experiments. The experimental system (Fig. 6) used in this study: computer with acquisition plaque DAQ 500, amplifier model 480B21 and three accelerometers type PCB 353B33. The sampling rate is 1/1200 per channel.

Work-pieces are made of aluminum alloy; the cutter is a three-edge-high-speed steel milling tool with a diameter of 25 mm. The trajectories are circular with continuous path. Cutting conditions were set as follows: spindle speed 1400 rpm for finish milling with axial depth of cut 0.5 mm per contour; spindle speed 710 rpm for rough milling; the cutting depth 10 mm.

5. EXPERIMENTAL RESULTS

The circular test provides a rapid and efficient way of measuring a machine tool's contouring accuracy. The circular tests show how the two axes work together to move the machine in a circular path. As the machine is traversing with multiple a xes along a circular trajectory,

Fig. 5. Photograph of the prototype measurement device.

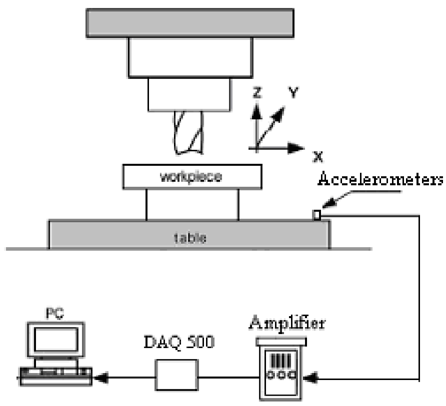


Fig. 6. Experimental set-up.

each axis goes through sinusoidal acceleration, velocity and position changes. The measured circular path data will show any deviation the machine makes from a perfect circle. The shapes are diagnosed and correlated to servo mismatch, backlash, squareness error, cyclic error, stick slip, machine vibrations, etc [10].

In order to investigate the influence of the interactions on the system performance circular motion trajectories are machined. Results of these processes make it possible to understand accurate dynamic behavior of a feed drive system.

The roughing, semi-finish and finish stages have very different requirements. In the roughing stage the goal is to remove material as rapidly as possible; large forces and tool deflections are permitted as long as the allowable tooth stress and the available spindle power are not exceeded.

During the semi-finishing stage, tool deflections are important since the goal of this stage is to create a uniform thickness for finishing. In the finishing stage tool deflections should be carefully controlled. Ideally, the cutting force should be held at a low constant value to achieve close tolerances and good surface finish [11].

For exemplification, two work-pieces with the same radius was machined, with different operating conditions, and can be observed that the amplitude of vibrations are bigger during roughing milling (Fig. 7) than finishing milling (Fig. 8). Cutting conditions were set as follows: for roughing milling spindle speed is 710 rpm and the feed rate – 120 mm/min; for finishing milling spindle speed – 1 400 rpm, feed rate – 250 mm/min with axial depth of cut 0.5 mm per contour, cutting depth 10 mm.

Table 1

r.m.s. values for different operating conditions

Operating conditions	**Feed rate [mm/min]**	**r.m.s. on *X* axis [m/s^2]**	**r.m.s. on *Y* axis [m/s^2]**
Roughing milling	120	1.09	1.04
Finishing milling	250	0.66	0.65

Machining circular path and comparing the roughing operation with finishing operation, the diagrams shows that the vibrations are two times higher for roughing than finishing process. This is noted in Table 1 where *r.m.s.* values were calculated for both cases.

From spectral analysis performed for the roughing and finishing operations was found that the dominant frequency values are the same for the *X* and *Y* axes involved in interpolation, only amplitudes are different owing to different cutting efforts. An example is presented in Fig. 9,*a* and *b*, for *X* axis, in both cases (roughing and finishing milling).

The same phenomenon happens on the other axis interpolation attend (*Y* axis in this case).

Vibrations during finishing milling process, when axis participating to the interpolation changes the direction of movement, are illustrated in Fig. 10 and 11. Acceleration amplitudes increase or decrease when the direction of feeding is change because the stiffness of the mechanical components of feed drive system is varying caused by pre-loaded and the values and direction of cutting forces are changed [12].

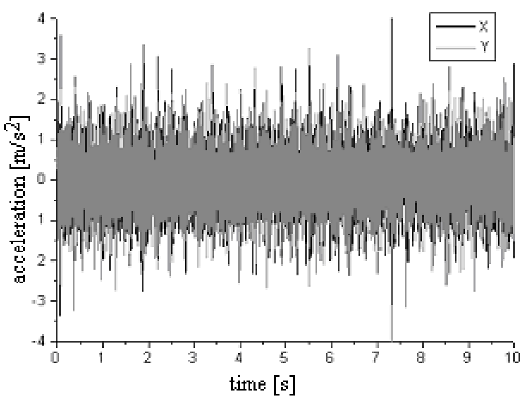


Fig. 7. Vibrations during roughing milling

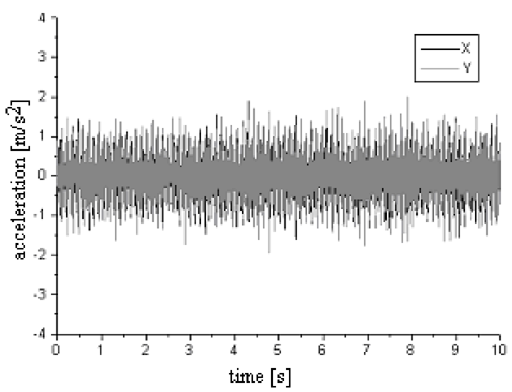
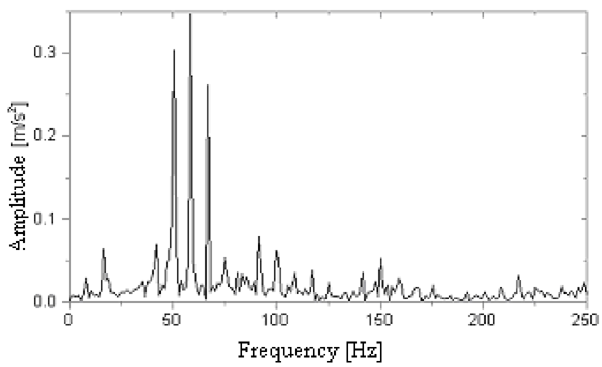
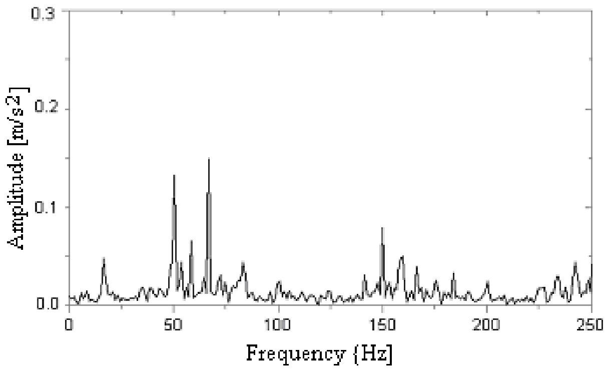


Fig. 8. Vibrations during finishing milling.



a



b

Fig. 9. Spectral analyses on X direction for: *a*) roughing milling; *b*) finishing milling.

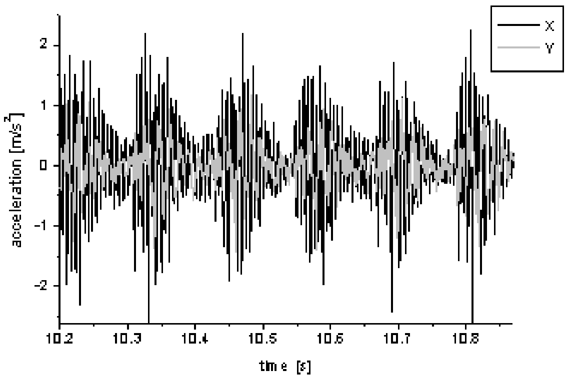


Fig. 10. Vibrations during milling process, when *X* and *Y* axis moving in one direction.

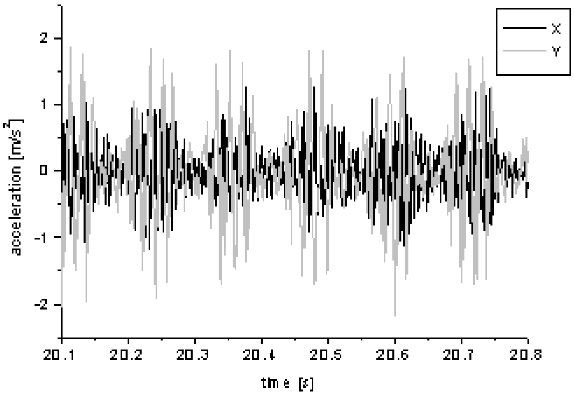
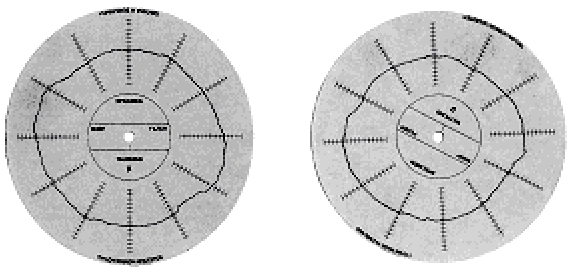


Fig. 11. Vibrations during milling process, when *X* and *Y* axis moving in the other direction.



a b

Fig. 12. Profilograms for circular trajectories; *a* – feed rate 150 mm/min; b) feed rate 300 mm/min.

To analyze the circular trajectory depending on the feed rate were processed two pieces with different feed rates: 150 mm/min and 300 mm/min.

In Fig. 11 are illustrated roundness and radial errors motion measurement under different feed rates. In the first case the circularity is 9 μm, in the second case the circularity is 12 μm. It can bee observe that errors are bigger when feed rate increase.

6. CONCLUSIONS

For high speed machining operations, machine tool contouring accuracy is very important. To achieve high quality and productivity, it is important to know for meeting the required accuracy which is the optimal feed rate. The standard verification of machine contouring accuracy is the use of circular tests.

The double ball bar method is widely accepted as a tool to measure the motion accuracy of NC machine tools and to diagnose their error sources. The DBB method can only perform circular tests due to its nature. Motion errors due to mistaking of CNC servo control systems are, however, often easier to observe on non-circular paths. For measuring the motion accuracy in arbitrary shape contouring, we have presented the KGM method and its advantages related to DBB method.

From experimental part of the paper, during the cutting process, we can observe that the contour errors depend on feed rate. The feed drive errors result from imperfection of machine control system. In order to realize high-performance of feed drive systems is required to analyze both mechanical and control system simultaneously. Therefore, machine feed drive is an integral part of a machine control system.

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