Improvement of the Machine Tools Performance

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Abstract: Machine tools performance from the point of view of compliance to tolerance, surface definition etc, is determined essentially by the dynamic and static accuracy of machine movement. This paper presents the dynamic behavior analyses for a vertical milling machine during milling process or without load. The experimental research shows vibrations transmission to the mechanical components of machine tool and theirs influence upon cutting process. In the same time, there are analyzed the evaluative factors of feed drive systems: geometrical errors, contour errors, stability of the cutting process, resonance frequency and structural deformation error, performances of the control system.

Key-Words: ball-screw, high speed machining, motion accuracy, contour errors, feed drive system, trajectory measurement, machine structure

1 Introduction

Machine tools are the most important means of production for the metalworking industries. Without the development of this type of machine, the high living standards of the present time would be unthinkable. In some of the most highly industrialized nations, approximately 10% of all machine built are machine tools, and about 10% of the work forces in machine manufacture are concerned with machine tools. Numerically controlled (*NC*) machine tools have been widely used for various purposes, such as for flexible automation, to improve machining accuracy, to reduce lead time, to cut cost etc. Therefore, the ability of *NC* machine tools should be improved in order to meet the various needs [10].

In recent years, the machine tools construction sector has been affected by strong international competition. As a result, companies in *NC* machine tool sector are under constant pressure to increase both the productivity and machining quality of their machines. Increasing both the machining speed and machining quality puts high demands on the dynamic and thermal behavior of the feed systems of modern machines [1].

Machine tools are complicated in their architecture and control and the price of machine tools varies from several thousand dollars to several million dollars depending on the purpose, performance and accuracy level.

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. For these reasons, in this paper there are analyzed evaluative factors of feed drive system to achieve high efficiency and high precision machining. In the same time, is analyzed the dynamic behavior of machine tool during the milling process.

2 Evaluative factors of feed drive

2.1 Geometric errors

The accuracy of the machine tool is primarily affected by the geometrical errors caused by mechanical-geometric imperfections, misalignments and wear of the linkages and elements of the machine tool structure, by the non-uniform thermal expansion of the machine structure and static/dynamic load induced errors. As a result a volumetric error, which is the relative error between the cutting tool and the work-piece, is created.

The errors can be reduced with the structural improvement of the machine tool through better design and manufacturing practices. Due to physical limitations, production and design techniques cannot improve accuracy. Therefore, identification and compensation of these error sources are necessary to improve machine tool accuracy.

In a feed drive system, the ball screw plays an important role as a power transmission unit and a linear scale. When a large speed of motion is demanded, the rate of feed of the ball screw transmission is much increased. Much heat is produced at both ends of the bearing support and the nut because of a greater speed of rotation. The accumulated heat causes the temperature to rise in these areas. Then the ball screw deforms thermally and has a seriously negative effect on the machine accuracy.

Semi-closed loop control systems are widely used in *CNC* machine tools. This control is of indirect position feedback type. For indirect control of position, the position of the table is recorded indirectly from the angular position of the ball screw or servomotor. The thermal errors of ball screw behind the measuring location are outside the control loop of the position.

In order to decrease thermal errors of this type, we use a pretension ball screw method, but for high-speed *CNC* machine tools, pretension can absorb only a small part of thermal error. For this reason, for determinations thermal errors it is necessary to attach thermocouples in the critical points of the machine tool. Through acquisition system, controller and *CNC* equipment the errors could be compensated [11].

Modern machine tools are equipped with packages for pitch error compensation and backlash compensation; these are applicable only under static conditions. In order to account for errors on a continuous basis in such a way that the interaction between the various error components could be considered, real-time error compensation system need to be employed.

The linear displacement errors, straightness errors, orthogonally errors, angular errors and non-rigid body errors determine the performance of accuracy of a *NC* machine tool. The characterization of a machine tool movement is very complex.

For each linear axis of motion, there are six errors, three linear displacement errors, and three angular errors (pitch, yaw and roll). Therefore, for a three-axis machine tool, there are eighteen errors represented in figure 1.

There is an angular error α_a if there is clearance between the ball-screw and nut of a feed drive system as shown in figure 2.

The distance D_a, Abbe offset, between the central axis of the ball-screw and the upper surface of a table, proportionally amplifies the angular error, which is the worst type of the geometric error in the feed drive system.

Abbe (offset) error is a linear positioning error resulting from angular components of movement in the linear positioning ways and the offset between a work-piece and the axis of measurement.

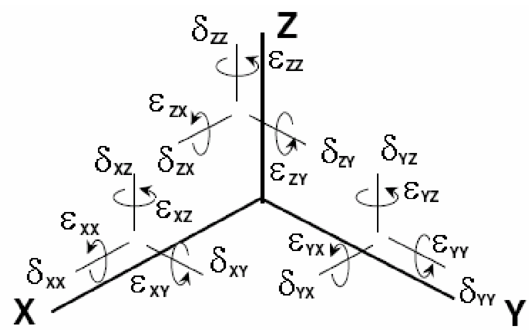


Fig. 1 Geometric errors in a feed drive system

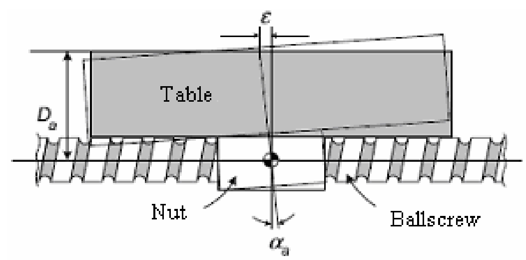


Fig. 2 Abbe error

The Abbe offset is represented as

$$D_a = h_{\mathrm{m}} + \frac{D_{\mathrm{Sc}}}{2} \qquad (1)$$

where: h_{m} is the height of the table and D_{Sc} is the ball screw diameter.

This result in an axial positioning error called Abbe error is noted ε. The actual Abbe offset D_{aa} will be used in the design process like double of the length of D_{a}.

$$D_{aa} = 2D_a = 2h_m + D_{Sc} \qquad (2)$$

Geometrical and thermal errors should be predicted through mathematical model. Using Rigid Body Kinematics, each axis of a machine tool relative to each other and to the reference frame can be modeled using a Homogenous Transformation Matrix [5].

The volumetric error compensation components such calculated, these values are introduced in the controller of the machine tool and correct the path error in teal time [7].

2.2 Contour errors

Accuracy can be defined as the degree of agreement or conformance of a finished part with the required dimensional and geometrical accuracy.

Error can be understood as any deviation in the position of the cutting edge from the theoretically required value to produce a work-piece of the specified tolerance.

Extend 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) [3].

The contour error for straight paths is:

$$\varepsilon_c = E_x \cdot \sin\alpha - E_y \cdot \cos\alpha \quad (3)$$

where E_x and E_y are the axis position errors and α is the angle between the tangent of the instantaneous trajectory and the X axis.

For curved paths (fig. 3), the contour error is

$$\varepsilon_c = E_x \cdot \sin\alpha - E_y \cdot \cos\alpha + r_i \cdot (\sec\gamma - 1) \quad (4)$$

where the angle γ is a function of the delay between the reference point and the tool position and the instantaneous curvature radius of the trajectory, r_i.

$$\gamma \cong \frac{\sqrt{E_x^2 + E_y^2}}{r_i} \quad (5)$$

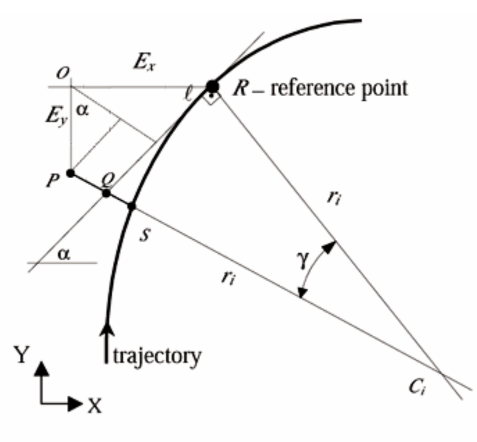


Fig. 3 The contour error

Recently, it has been reported that the accuracy of a linear motion around the square corner can be regarded as an important index to evaluate the performance of *NC* machine tools [6].

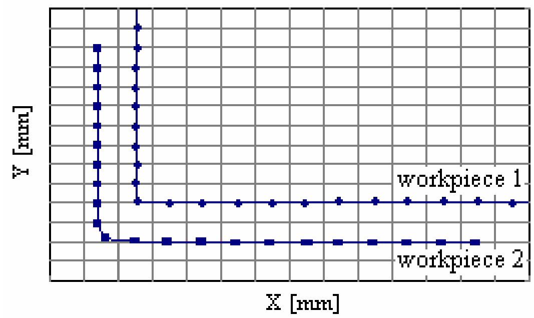


Fig. 4 Square corner error

In order to examine the effects of feed rates, two work-pieces are machined with different feed rates (200 mm/min; 800 mm/min) and measured than with a control machine, ZEISS, around the square corner. The results are presented in figure 4, where is clearly observed that corner error increased with feed rate.

2.3 Stability of the cutting process

Any dynamic characteristic in the machine tool will lead to the generation of vibrations, the effect of which can lead to poor surface finish on the work-piece, increased machine tool were, as well as tool fracture and damage to both the work-piece and machine.

The machining process is shown in figure 5 as a closed loop wherein the flexibility of the machine is represented in the forward branch and the cutting process in the return link.

The behavior of the machine is indicated by "directional flexibility – frequency characteristic $G_d(j\omega)$" which takes the geometric conditions of the machining process under consideration into account (the relative position of the work and tool), the cutter geometry and the number of cutting edges of the tool being used [12]. It represents the relative movements in the direction of the chip thickness between the work and tool caused by the dynamic cutting force.

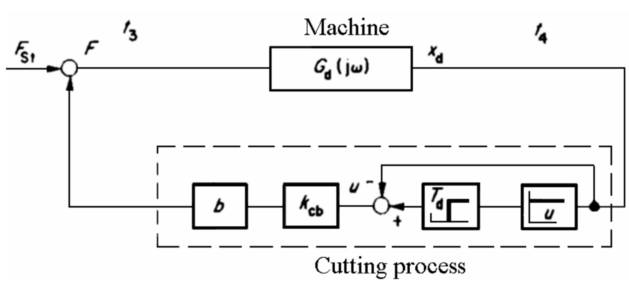


Fig. 5 Machining process

Even under continuous machining conditions, relative movements take place between the work and cutting tool, which will interfere with the required nominal motions (the feed and the cutting movements). For the evaluation of these vibratory movements, it is usual to differentiate between externally excited or forced vibrations and self-excited oscillations.

Self-excitation vibrations occur as a result of the surface finish waviness introduced by the externally excited vibrations, which lead to excitations (self-excitations) after the work has made one revolution in the case of turning or when the next cutting tooth engages in the case of milling operations. These vibrations caused by the regenerative effect are mainly a dynamic problem in metal-cutting machine tools [12]. All these errors in the machine tools interact with each other and make a complex situation for error compensation research.

The effect of the machine and the cutting process upon the chatter conditions can be obtained from a consideration of the stable state of the closed loop machine-cutting process. By applying the "Nyquist criterion" for the stability loop, the following conditions must be satisfied for the frequency characteristic of the open loop

$$\mathrm{Re}\{G_0(j\omega)\} \begin{cases} < 1 \text{ stable} \\ = 1 \text{ stability boundary} \\ > 1 \text{ unstable} \end{cases} \qquad (6,a)$$

$$\mathrm{Im}\{G_0(j\omega)\} = 0 \qquad (6,b)$$

The relationship for the speed-dependent dead-time T_t as $\omega = 2\pi f$

$$T_t = \frac{1}{\pi f}\left\{\arctan\left(-\frac{\mathrm{Re}\{G_g(jf)\}}{\mathrm{Im}\{G_g(jf)\}}\right) + m\pi\right\} \qquad (7)$$

where $m = 1,2,3...\infty$;

In this condition the machine will tend to chatter as soon as a given limiting chip width b_{cr} is exceeded. If the speed of rotation and the number of cutting edges are considered, we obtain the following equation

$$n = \frac{60}{zT_t} = \frac{60 \cdot f}{z \cdot \left(m - \frac{1}{\pi} \cdot \arctan\frac{\mathrm{Re}\{G_g(jf)\}}{\mathrm{Im}\{G_g(jf)\}}\right)} \qquad (8)$$

Using equation (8), for every possible chatter frequency series of critical machine speeds can be identified in relationship to the phase angle, described by the real and imaginary component of the directional flexibility – frequency characteristic $G_d(j\omega)$. The actual chip width b determines whether the machine will chatter at the various speeds. When b exceeds a limiting critical chip width b_{cr}, the cutting process becomes unstable.

The relation for critical chip is

$$b_{cr} = \frac{1}{2k_{cb}\left|\mathrm{Re}\{G_g(jf)\}_{\mathrm{neg}}\right|} \qquad (9)$$

Any dynamic characteristics in the machine tools lead to the generation of vibrations, the effects of which can lead to poor surface finish on the work piece increased machine tool wear, tool fracture and damage to both, the work piece and machine.

Under continuous machining conditions, two types of vibrations occur: externally excited and self-excited vibrations.

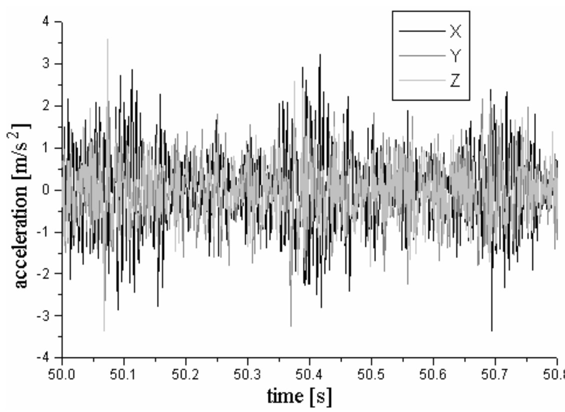


Fig. 6 Vibrations during roughing milling

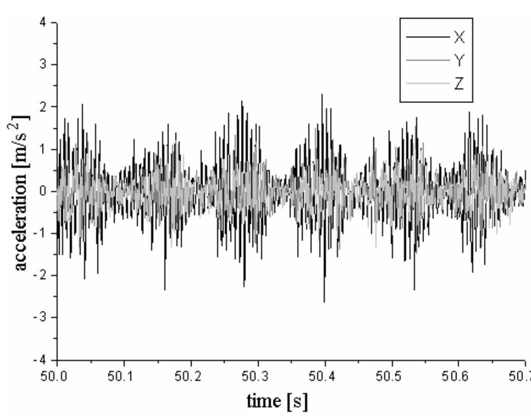


Fig. 7 Vibrations during finishing milling

For exemplification, two work-pieces are machined with different operating conditions and can be observed that amplitude of vibrations are bigger during roughing milling (fig. 6) than finishing milling (fig. 7).

2.4 Resonance frequency and structural deformation error

Machine tools consist of a multitude of mechanical components coupled together. Each of these spring/mass systems causes a resonance increase on the flexibility. In general, frequencies at which such resonance increases occur are known as *resonance frequencies.* The position at which the absolute maximum flexibility takes place is therefore called the *dominant resonance position* and the associated frequency is known as the *dominant resonance frequency.*

Since the critical speed of a drive system leads to resonance, the critical speed of a ball-screw shaft estimated from the natural frequency of a bar element, where the fixed-ends boundary condition is applied, must be included in the integrated design procedure [2].

The critical speed v_c is given by

$$v_c = \frac{p}{2\pi}\omega_0 = \frac{11{,}2\, D_{sc}\, p}{\pi L_{sc}^2}\sqrt{\frac{E_{sc}}{\rho_{sc}}} \qquad (10)$$

where ω_0 and ρ_{sc} are the natural frequency and density of a ball-screw shaft, respectively, p – the ball-screw pitch, L_{sc} – ball-screw length, D_{Sc} - ball screw diameter.

Developed design methodology gives not only the possibility to evaluate and optimize the dynamic motion performance of the feed drive system, but also improves the quality of the design process to achieve the required performance for high-precision/speed feed drive systems.

So, a beam model on elastic foundations (fig. 9) is considered to derive structural deformation error. The dimensions of linear guides are dependent on table dimensions and stroke of a feed drive system as follows

$$l_g = \frac{2}{3} l_m\,,\ L_g = 2\cdot L_{str} \qquad (11, a, b)$$

The spring constant of linear guides on elastic foundation is given by

$$k_e = \frac{48\, E_g\, I_g}{l_g\, L_g^3} = \frac{48\, E_g\, I_g}{\frac{2}{3} l_m (2\, L_{str})^3} = \frac{9\, E_g\, I_g}{l_m L_{str}^3} \qquad (12)$$

The deformation error of a mechanical structure in a vertical direction is described as follows

$$\delta_c = \frac{\beta}{2 k_e}\left(\frac{2+\cos\beta\cdot l_m + \cosh\beta\cdot l_m}{\sin\beta\cdot l_m + \sinh\beta\cdot l_m}\right)\cdot F \qquad (13)$$

where $\beta = \left(\frac{k_e}{4 E_m I_m}\right)^{1/4}$

Moment of inertia of the table is calculated as

$$I_m = \frac{L_m\, h_m^3}{12} \qquad (14)$$

From equations (12) and (14) we obtain

$$\frac{\beta}{2k_e} = \left(\frac{1}{64\, E_m\, I_m\, k_e^3}\right)^{1/4} = \frac{l_m L_{str}^3}{18\, E_g\, I_g}\left(\frac{27\, E_g\, I_g}{E_m\, L_m\, l_m\, L_{str}^3\, h_m^3}\right)^{1/4} \qquad (15)$$

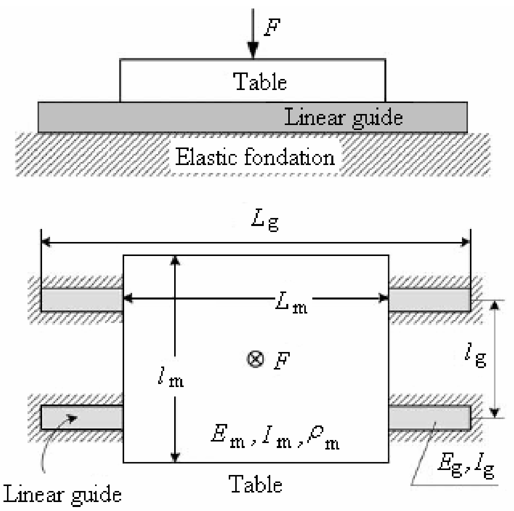


Fig. 9 A beam model on the elastic foundation

The deformation error of a mechanical structure in the vertical direction including the Abbe offset is described as follows

$$\delta_c = \frac{l_m L_{str}^3}{3 E_g\, I_g}\left(\frac{E_g\, I_g}{6\, E_m\, L_m\, l_m\, L_{str}^3 (D_{aa} - D_{sc})^3}\right)^{1/4} \times\left(\frac{2+\cos\beta\cdot l_m + \cosh\beta\cdot l_m}{\sin\beta\cdot l_m + \sinh\beta\cdot l_m}\right)\cdot F \qquad (16)$$

where F is the external force acting on mechanical components added to the external force due to the table and the work-piece mass.

Using equations (10) and (16) and processed information from table 1, the critical speed and the deformation error for *X* axes are

$$v_c = 612\ m/s\,;\ \delta_c = 20{,}5\cdot 10^{-6}\ \text{m}$$

Table 1
Parameters of milling machine used for experiments

Parameters	Symbol	Dimensions
Ball-screw diameter	D_{sc}	0,04 m
Ball-screw pitch	p	0,01 m
Ball-screw length	L_{sc}	1,1 m
Ball-screw density and table density	ρ_{sc}, ρ_m	7,8 kg/dm^3
Elastic modulus of the ball-screw	E_{sc}	$2{,}1 \cdot 10^9$ N/m^2
Shear modulus of the ball-screw and coupling	G_{sc}, G_{cp}	$8{,}1 \cdot 10^{10}$ N/m^2
Moment of inertia of the ball-screw	I_{sc}	$12{,}56 \cdot 10^{-8}$ m^4
Nut stiffness	k_p	$720 \cdot 10^6$ N/m
Stiffness of the support bearing	k_l	$1500 \cdot 10^6$ N/m
Table length	L_m	1,4 m
Table width	l_m	0,9 m
Elastic modulus of table and linear guide	E_m, E_g	$(1{,}15 \div 1{,}6) \cdot 10^9$ N/m^2
Moment of inertia of the table	I_m	$14{,}32 \cdot 10^{-4}$ m^4
Length of the linear guide	L_g	2,2 m
Distance between linear guides	l_g	0,6 m
Moment of inertia of linear guides	I_g	$3{,}255 \cdot 10^{-4}$ m^4
Stroke of the feed drive system	L_{str}	1,1 m
Maximum load applied on the table	F	20000 N

2.5 Performances of the control system

In order to improve servo controller's performances, various control techniques were applied to *NC* machine tools in the past years [4].

Nowadays, there are many advanced controllers on the market that can realize greater error compensation in an improved way. Siemens 840 D controllers can compensate for temperature effects. The interpolator compensation function allows position-related dimensional deviations to be corrected.

The Heidenhain controller has similar functions, errors in machine geometry or external influences (e.g. temperature) can cause non-linear axis errors which can be compensated by *iTNC* controllers.

Control strategies used for *NC* machine tools are: Feed Forward Control, Cross Coupling Control and Optimal Control. Optimal Control is further broken down into Predictive Control, Adaptive Control and Learning Control [9].

While *P*, *PID*, state-feedback and feed-forward controllers are intended to reduce the axes positioning errors, the contour error controller had the philosophy that its unique objective is the elimination of the contour error. It helps and works together with the machine axes controllers (fig. 10).

The problems with this kind of controllers are the necessity of a fast processor to do real time calculations and the lack of accuracy when tracking non-linear contours at high speeds.

The first problem is being solved by the evolution of the microprocessors. An additional term is introduced in the contour error mathematical model in order to make better contour error estimation in high speed contouring operations [8].

The contour error controller consists of two main parts: the first is the contour error model, which is used to calculate the table path deviation in real time and the second is the control low, which send appropriate correction signals to the individual axes. The control law can be a *P*, *PID*, Fuzzy Logic or another type of controller.

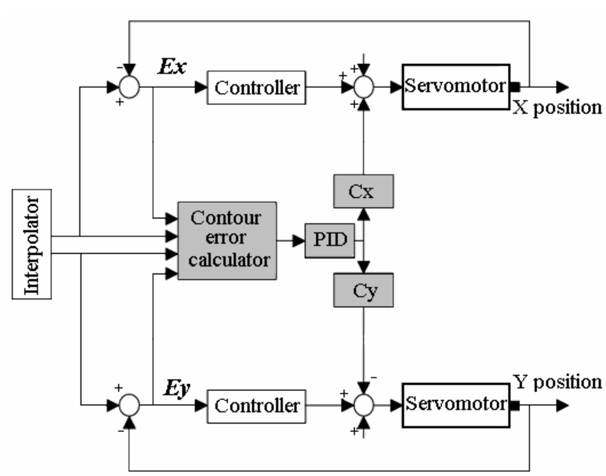


Fig. 10 Block diagram of two axes numerically controlled

Note that there is a coupling between the axes. The interpolator sends reference command signals to each axis that are compared with the actual positions.

The resulting tracking errors feed the axes controllers, whose function is to move the tool to the reference point, thus reducing these errors. The contour error calculator block utilizes the interpolator data and error signals to calculate the contour error in real time.

Contour error motion controllers where designed in the beginning of 1980 by Koren to improve machine tool contouring performance [3]. The sources of path error deviation in machine tools are classified into three categories: mechanical hardware deficiencies (backlash, non-straightness etc), cutting process effects (tool deflection, tool wear, thermal deformation, etc) and the controller and drive dynamics. The total dimensional error is a combination of the errors from these sources. Improving the quality of the mechanical hardware or using compensation techniques can minimize the first and the second error sources. The third set of error sources can be reduced by improving the motion control algorithms.

3 Experiments

3.1 Experimental set up

The accuracy of work produced on metal cutting machine tools is determined by the deviations at the cutting point from the required working movements between the tool and work-piece. These deviations are caused - in addition to geometric and kinematics errors - by the static and dynamic forces deforming all the components which are in the force-flux flow of the machine, such as machine frames, beds, slides, spindles etc.

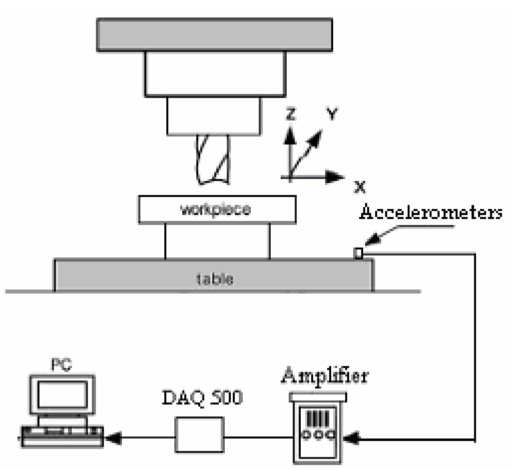


Fig. 11 Experimental set-up

In contrast, any uneven dynamic characteristics will lead to the generation of vibrations, the effects of which can lead to poor surface finishes on the work, increased machine and tool wear, as well as tool fractures and damage to both the work-piece and the machine. With this in mind, the flexibility characteristics of the machine in relation to changing load conditions must be regarded as a criterion of the performances capability [12].

So, a three-axis milling machine is used for the experiments. The experimental system used in this study: computer with acquisition plaque DAQ 500, amplifier model 480B21 and three accelerometers type PCB 353B33 mounted on the table (fig. 11). The sampling frequency is 1200 Hz per channel.

Work-pieces are made of aluminum alloy; the cutter is a three-edge-high-speed steel-milling tool with a diameter of 50 mm.

3.2 Experiments without load applied

Experiments are made on a vertical milling machine with accelerometers fitted on the table, moving the carriage along working stroke.

The carriage was driven forward and backward without load applied on *X* and *Y* axes. Amplitude-frequencies characteristics during carriage moved on *X* axis with feed rate 300 mm/min is presented in figure 12, and for *Y*-axis is presented in figure 13.

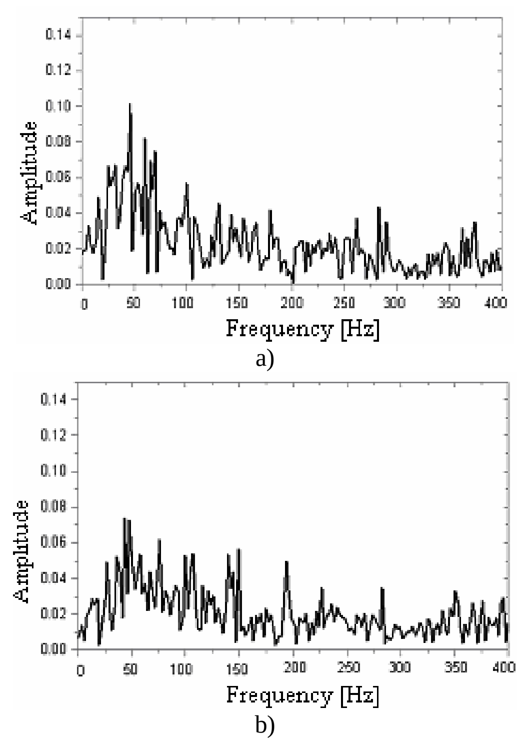
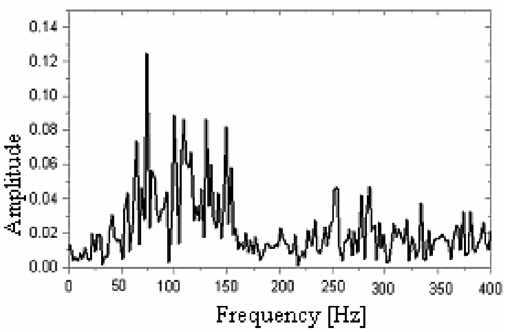
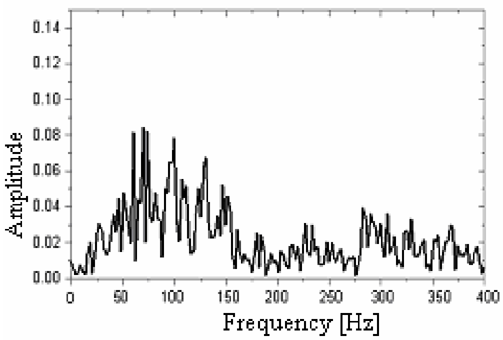


Fig. 12 Amplitude-frequencies characteristics for *X*-axis moving table: a) forward direction; b) backward direction.



a)



b)

Fig. 13 Amplitude-frequencies for *Y*- axis moving: a) forward direction; b) backward direction

Comparing the forward and backward movement, the amplitudes increase or decrease when the direction is changed because the stiffness of the mechanical components of feed drive system is varying caused by pre-loaded.

With accelerometers mounted on the housing spindle, with spindle shaft out to 1/3 of his length, we have measured the vibrations for different speeds. The axes position of the machine tool during tests is presented in figure 14.

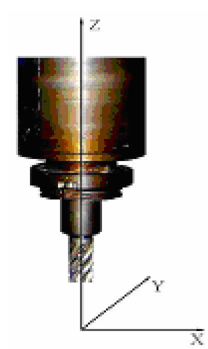


Fig. 14 Axis position during measurement

Figure 15 shows the vibrations on axis *X*, *Y*, *Z* for spindle speed 710 rpm. In this figure, we can observe the accelerating/braking parts and constant motion in no-load conditions.

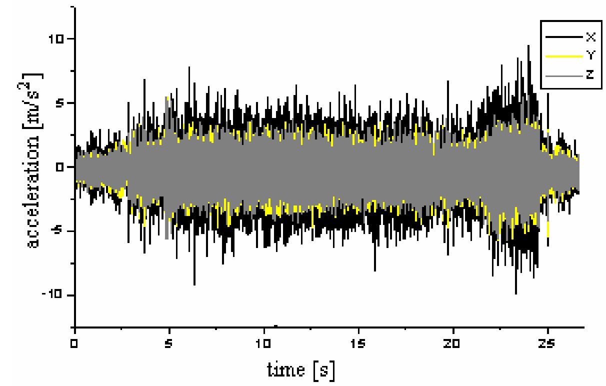


Fig. 15 Vibrations during spindle rotation with 710 rpm

The vibrations are lower in *Z* direction, because the spindle is situated in a vertical position and the unbalance caused by imprecision assembly and the execution are manifested in *X* and *Y* directions.

3.3 Experiments during milling process

Under continuous machining conditions relative movements take place between the work and cutting tool, which will interfere with the required nominal motions, i.e. the feed and cutting movements.

In order to investigate the influence of the interactions on the system performance, linear and 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.

Cutting conditions were set as follows: for roughing milling spindle speed is 710 rpm and the feed rate - 150 mm/min; for finishing milling spindle speed – 1400 rpm, feed rate – 300 mm/min, axial depth of cut 0.5 mm per contour and radial width of cut 10 mm.

The scheme used for signal processing, using LabVIEW software, for all applications of the paper, is presented in figure 16.

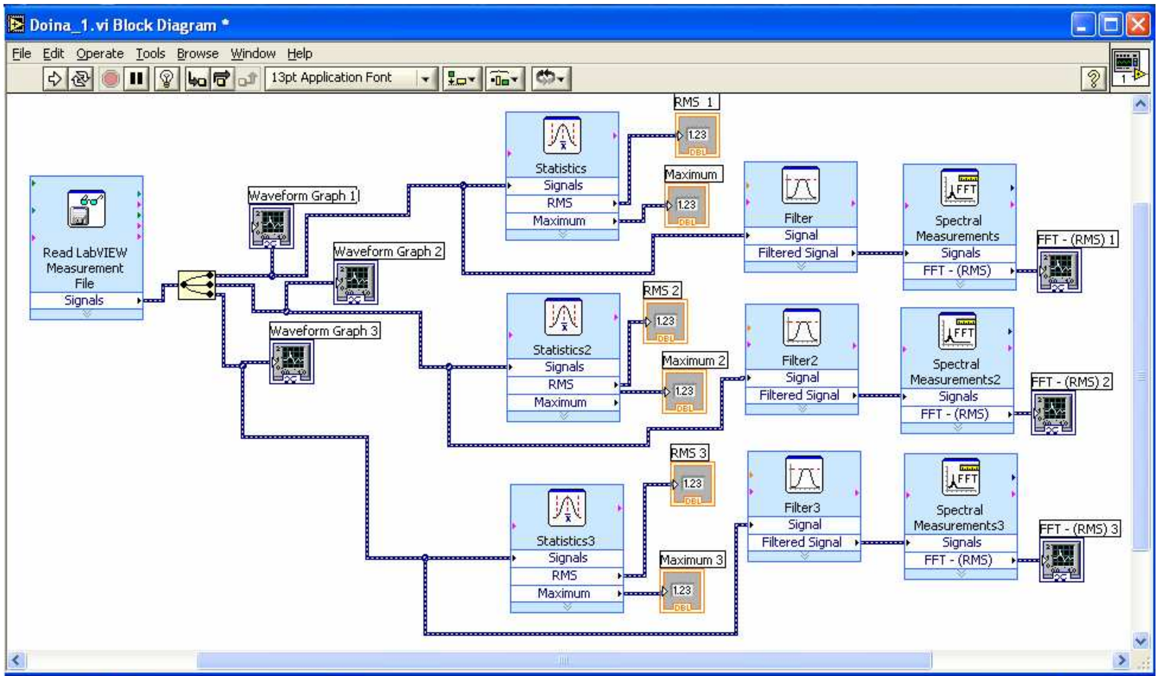


Fig. 16 Signal processing scheme

Linear or circular test provides a rapid and efficient way of measuring a machine tool's contouring accuracy.

For *NC* machine tools, during milling process of a continuous path, the tool is positioned tangent to the trajectory and performs a contour identically with programmer contour equidistant with tool radius. During roughing milling, according to machining allowance, tool cut more or less material as is shown in figure 17.

The feed rate (acceleration) data with respect to different positions in the trajectory were recorded using accelerometers for each axis that participate to interpolation (*X* and *Y*-axes of the machine tool). Linear motion trajectories near square corner during roughing milling have been analyzed in figure 18. It can be observed the decrease of the acceleration on the axes participating to the interpolation, acceleration increasing when the tool enter in semi-finished material again.

On the other hand, while approaching the corner, the speed is reduced along the first linear motion. With a little delay, the second linear motion starts.

The cause of corner errors while approaching a corner was examined in this paper during finishing milling along two consecutive linear motions containing a right angle.

From figure 19 the increasing and reducing processes in feed speed near the corner are clearly observed.

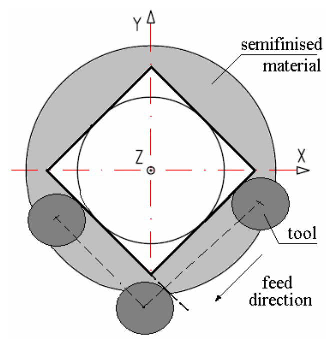


Fig. 17 Tool trajectory in semi-finished material

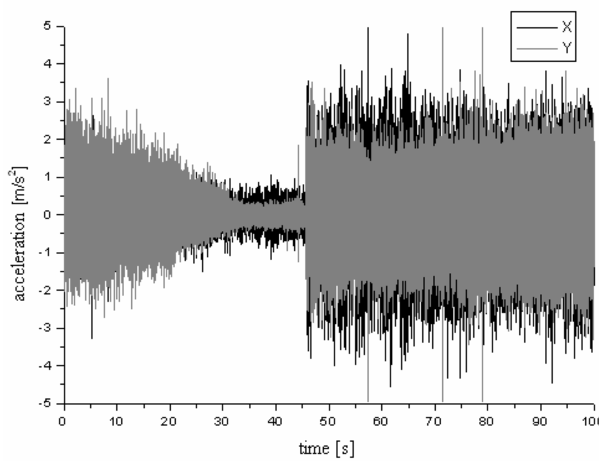


Fig. 18 Vibrations on *X* and *Y* axis during heavy milling

While approaching the corner, the feed rate is reduced along the first linear motion. With a little delay, the second linear motion starts. Because of the inertia of the driving system, increasing the speed to a specified value for the second motion and reducing the speed to zero for the first motion instantaneously are impossible. Therefore, if no dwell between both linear movements has been specified, there is an overlap between the speed reducing process of the first motion and the speed increasing process of the second motion around the corner. As a result, the overlap effect caused the corner error.

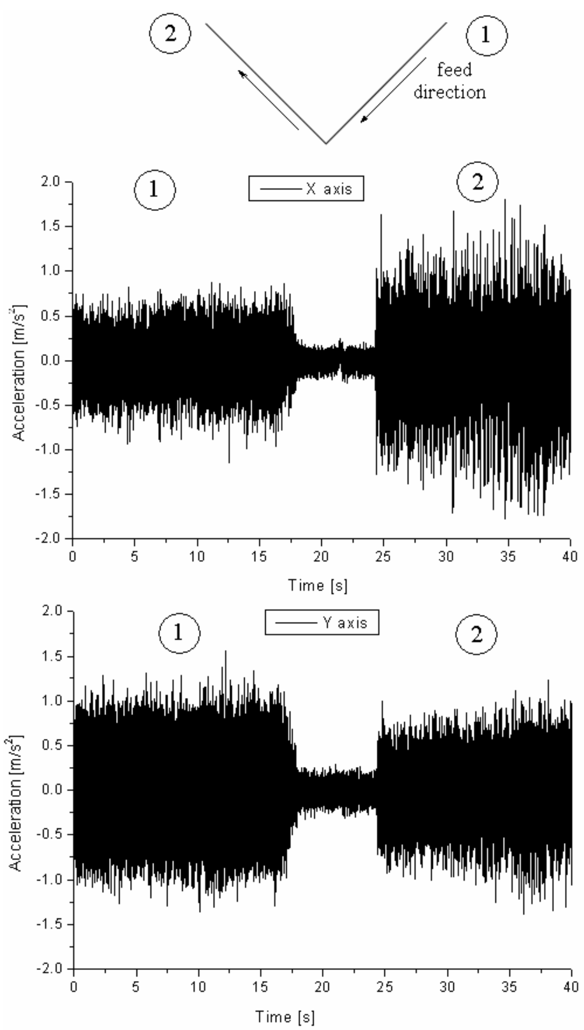


Fig. 19 Vibrations on *X* and *Y* axis during cutting process with feed rate 200 mm/min.

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

Vibrations during finishing milling process, when axis participating to the interpolation changes the direction of movement, are illustrated in fig. 20 and fig. 21. 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.

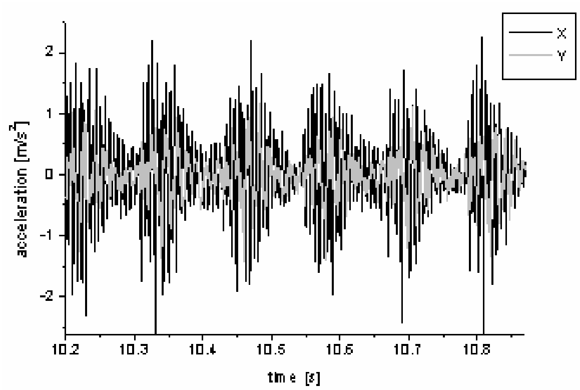


Fig. 20 Vibrations during milling process, when *X* and *Y* axes moving in one direction

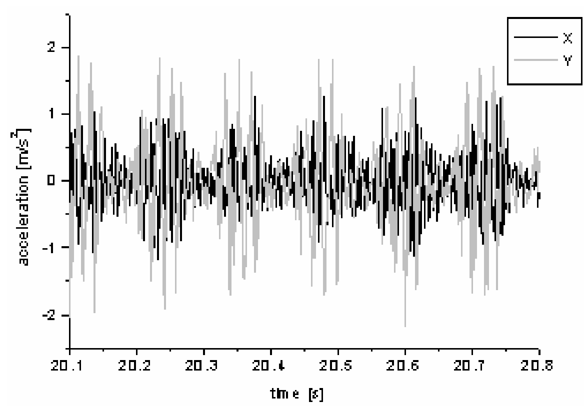


Fig. 21 Vibrations during milling process, when *X* and *Y* axes moving in other direction

On the other hand, circular trajectory is machined with feed rate 150 mm/min and spindle speed 710 rpm, with accelerometers mounted on the work-piece device (fig. 22) and on the housing spindle (fig. 23). Comparing these figures, we have observed that the accelerations on the *X* and *Y* axes (participating to the interpolation) are almost equally and on the *Z* axis are twice or more bigger, the cause is cutting efforts during end milling.

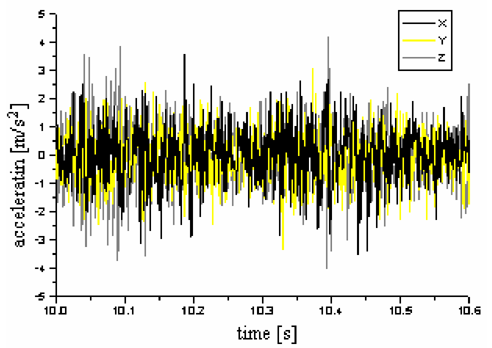


Fig. 22 Vibro-records during cutting process with accelerometers mounted on the workpiece device

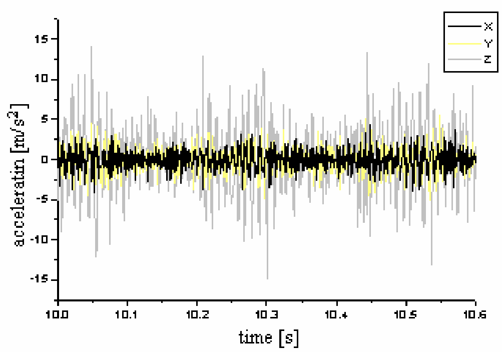


Fig. 23 Vibro-records during cutting process with accelerometers mounted on the housing spindle

4 Conclusions

The paper has investigated all three axes of milling center. During movement without load, on the *X* and *Y* axis, we have observed that acceleration amplitudes increase or decrease when the direction of feeding is changed because the stiffness of the mechanical components of feed drive system are varying function of pre-loaded. The same thing is happening during the cutting process because the values and directions of cutting forces are changed. On *Z* direction, the acceleration is bigger because during end milling the cutting efforts increase in this direction.

Feed drive errors were evaluated along a square corner path. The experimental results verify that the cause of corner errors in contour manufacturing is due to the increase and reduction in feed speed near the connection position between two linear motions to form the corner.

It was determined that contour errors increased with feed rate, at a rate that escalates with curvature.

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 subsystems simultaneously. Therefore, machine feed drive is an integral part of a machine control system.

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