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IMPROVING CNC MACHINE TOOLS ACCURACY BY MEANS OF THE CIRCULAR TEST AND SIMULATION

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Abstract: *This paper presents a method for improving the accuracy of CNC machine tools by means of a joint approach: experimental tests and simulation. In the first stage, a circular test was performed, by means of a special measuring device. The errors shown by the measurements were evaluated and possible causes were assessed. After running a simulation process, which took into consideration the phenomena which may cause the errors, possible solutions for reducing the errors were proposed. Finally, new measurements validated some of the solutions. The proposed approach is indented to be use at the shop floor level, so it was kept as straightforward and fast as possible.*

Key words: *accuracy, circular test, ballbar transducer, CNC machine tools, simulation*.

1. INTRODUCTION

Computer numerically controlled (CNC) machine tools have played an important role in precision machining. In recent years, machine tool builders have been under increasing pressure from the manufacturing industry to provide a higher contouring accuracy for a multi-axis CNC machine tool.

The increasing demand for higher dimensional accuracies and the strong trend toward shop floor automation induce the need to develop cost-effective methods to improve the performance of CNC machine tools. The dimensional accuracy of machined parts is one of the most important factors in determining this performance. In multi-axis machines such as machine tools, coordinate measuring machines and robots, it is often difficult to achieve the desired accuracy due to the complexity and the interactions of the various error sources.

2. CIRCULAR TEST

To achieve high-precision machining, CNC machining centres must have contouring accuracy. Therefore, a measurement method to assess the contouring accuracy of CNC machine centres has to be established. In recent years, a circular test has been developed to measure and diagnose contouring errors of CNC machine tools [1−6].

The circular test is a widely used method to measure motion errors of CNC machining centres. During the test, a circular path is generated by a CNC controller and a transducer bar is mounted between the machine spindle and table. As the machine travels around the circular path, the bar measures the deviations relative to a standard circle. The deviations can then be used to indicate the motion errors of CNC machining centres.

For this research, a Renishaw QC10 ballbar system was used (Fig. 1). The system and its software is used to measure geometric errors present in a CNC machine tool and detect inaccuracies induced by its controller and servo drive systems.

Errors are measured by instructing the machine tool to 'Perform a Ballbar Test' which will make it scribe a circular arc or circle. Small deviations in the radius of this movement are measured by a transducer and captured by the software. The resultant data is then plotted on the screen or to a printer or plotter, to reveal how well the machine performed the test.

If the machine had no errors, the plotted data would show a perfect circle. The presence of any errors will distort this circle, for example, by adding peaks along its circumference and possibly making it more elliptical.

These deviations from a perfect circle reveal problems and inaccuracies in the numerical control, drive servos and the machine's axes.

During the data capture session, the Ballbar moves in a clockwise and counter-clockwise direction through 360° data capture arcs with 180° angular overshoot arcs.

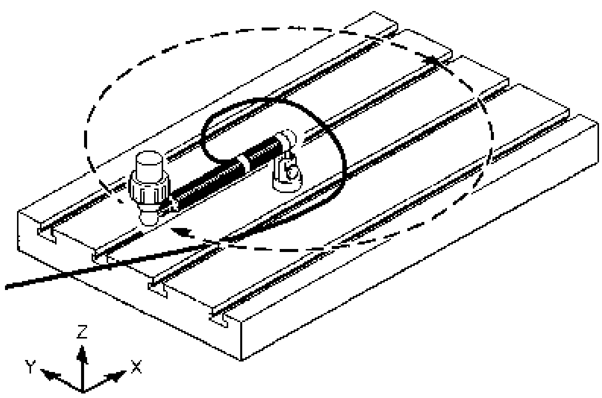

Fig. 1. The ballbar system.

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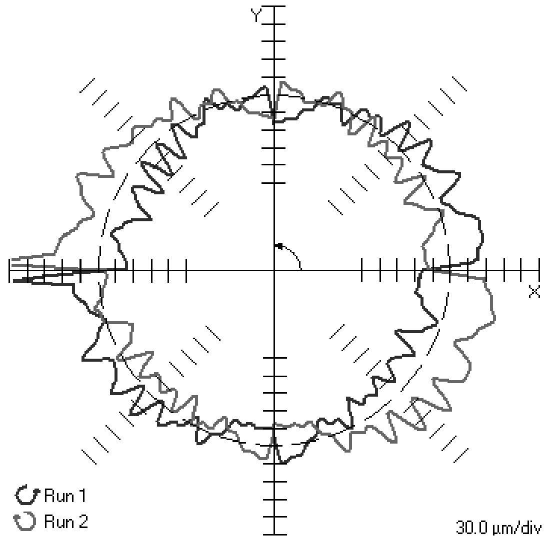

Fig. 2. The initial measurement.

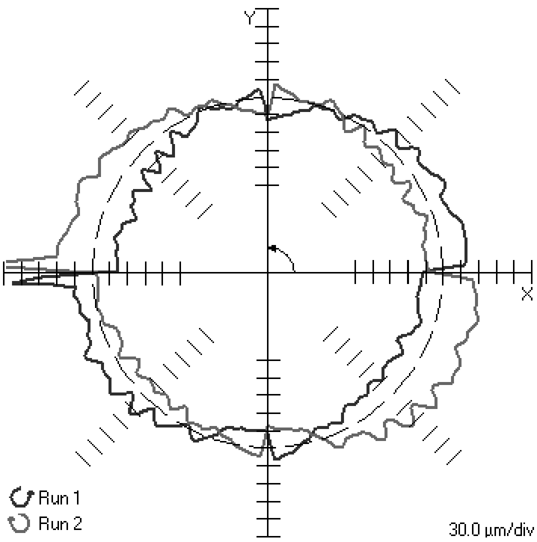

Fig. 3. The second measurement after a mechanical adjustment of the encoder mountings.

Figure 2 shows an initial measurement result on a Realmeca C2 vertical machining center. After running the software analysis, three main groups of errors were reported:

- Cyclic error, of about 40 µm on each axis;
- Backlash error of about 60 µm on *X*-axis and 40 µm on *Y*-axis:
- Reversal spikes on *X* axis of about 200 µm.

The possible causes for the cyclic error could be: the axis ballscrew thread is defective causing the axis to move in a sinusoidal manner rather than at a uniform rate, or the encoder mountings may be eccentric, or the ballscrew mountings may be eccentric or badly adjusted resolvers or inductosyns.

After a mechanical adjustment of the encoder mounting, a second measurement was performed. The results are presented in Fig. 3. A significant improvement in the results is noticeable, further compensation steps are necessary.

A backlash compensation algorithm is included in CNC equipment software.

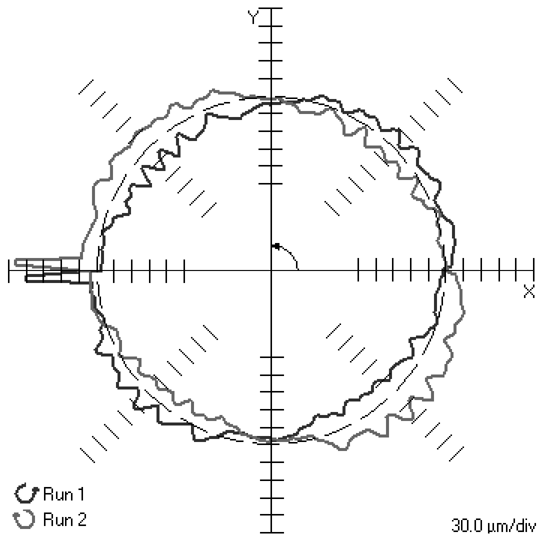

Fig. 4. The third measurement after backlash compensation.

The algorithm allows the user to introduce the maximum value of the backlash on each axis and the CNC controller will compensate it.

After this compensation step, a ne w measurement was performed (Fig. 4). The remaining significant error is the reversal spikes on *X* axis. In order to find a compensation method, the possible causes have to be analyzed. Reversal spikes appears when an axis is being driven in one direction and then has to reverse and move in the opposite direction, instead of reversing smoothly it may pause momentarily at the turnaround point. There are several possible causes of this problem:

- An inadequate amount of torque has been applied by the axis drive motor at the axis reversal point causing it to stick momentarily at the reversal point, as the frictional forces change direction.
- The servo response time of the machine is inadequate on backlash compensation. This means that the machine is unable to compensate for the backlash in time; causing the axis to stop while the slack caused by the backlash is being taken up.
- Servo response at the crossover point is poor, causing a short delay between the axis stopping movement in one direction and starting movement in the other.

3. THE MODEL OF THE SYSTEM

In order to find a solution to compensate the reversal spikes, a study of the feed chain of the *X*-axis, assimilated as a closed loop position by means of a simulation process was proposed.

The first approach in studying the systems behaviour is to build a reliable model of it, based upon transfer functions. One of the steps involves the description of each axis of movement as a position control servo system. Generally, such kind of system, no matter which actuation system is used, has a schematic structure as depicted in Fig. 5.

The relation between the angular speed of the DC servomotor ω and the input voltage *U*, with regards of the complex variable *s*, can be expressed as [7 and 8]:

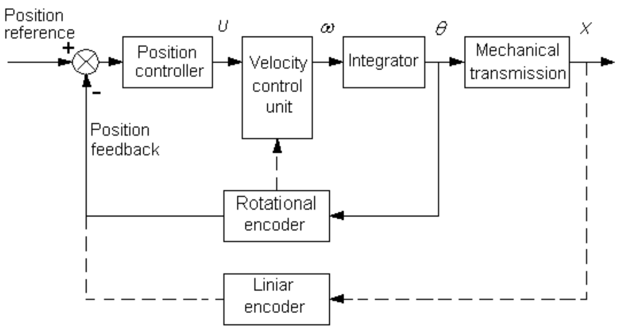

Fig. 5. Schematic structure of a position control servo system.

$$\omega(s)=\frac{\alpha}{1+\tau\cdot s}[U(s)\frac{K_aK_t}{RB+K_tK_v}-\\ -\frac{R}{RB+K_tK_v}M_s(s)], \tag{1}$$

where:

R – motor armature winding resistance [Ω];

J_r – rotor inertia [kgm^2];

B – viscous friction constant [Nms/rad];

K_t – motor torque constant [Nm/A];

K_v – velocity constant [Vs/rad];

K_a – the amplifier gain;

K_{th} – tachometer gain [Vs/rad];

τ_m – mechanical time constant [s] which can be expressed as:

$$\tau_m=\frac{RJ}{RB+K_tK_v}, \tag{2}$$

$$\tau_e=\alpha\tau_m . \tag{3}$$

where:

τ_e – electrical time constant of the motor;

α – the attenuation factor.

Then the motor speed can be expressed in the following form:

$$\omega(s)=\frac{K_1U(s)-K_2M_2(s)}{1+\tau s}. \tag{4}$$

where:

$$K_1=\frac{\alpha K_aK_t}{RB+K_tK_v}\ \text{[rad/Vs]}. \tag{5}$$

$$K_2=\frac{\alpha R}{RB+K_tK_v}\ \text{[rad/Nms]}. \tag{6}$$

Equation (4) shows the components of the transfer function of the closed velocity loop: one transfer function between the input voltage and the motor speed and one between the static torque (disturbance) and the motor speed, leading to the following:

$$H_0(s)=\frac{\omega(s)}{U(s)}=\frac{K_1}{1+\tau s}. \tag{7}$$

and

$$H_{0P}(s)=\frac{\omega(s)}{M_s(s)}=\frac{K_2}{1+\tau s}. \tag{8}$$

Considering the voltage input and the static moment as step inputs and applying the Laplace transform to these inputs:

$$U(s)=\frac{1}{s}\ U. \tag{9}$$

$$M_s(s)=\frac{1}{s}\ M_s. \tag{10}$$

then the motor speed $\omega(t)$ is given by the following expression:

$$\omega(t)=(\frac{\alpha K_aK_t}{RB+K_tK_v}U-\frac{\alpha K_tR}{RB+K_tK_v}M_s)(1-e^{-\frac{t}{\tau}}). \tag{11}$$

The unknown factors in equation (11) are the amplifier gain K_a and the tachometer feedback K_p which is included in α. Imposing that for the maximum voltage U_m and for the maximum static load M_{sm}, the motor speed has to reach the maximum value ω_m, these two factors can be determined. The condition stated above characterizes the stationary regime of the system, when $t\rightarrow\infty$:

$$\lim_{t\to\infty}e^{-\frac{t}{\tau}}=0. \tag{12}$$

In this condition, equation (11) becomes:

$$\omega_m=\frac{\alpha K_aK_t}{RB+K_tK_v}U_m-\frac{\alpha K_tR}{RB+K_tK_v}M_{sm}. \tag{13}$$

Now we have to determine the analogical to digital converter gain K_c, the encoder gain K_e, and gear reducer gain K_g.

The encoder is characterized by the encoder gain K_e, defined as the number of pulses emitted for one rotation of the lead screw:

$$K_e=\frac{N_{imp}}{2\pi}\ \text{[pulses/rad]}. \tag{14}$$

where:

N_{imp} – number of the pulses emitted by the encoder at a full rotation.

The gear reducer gain K_g can then be expressed as:

$$K_g=\frac{ip}{2\pi}\ \text{[m]}. \tag{15}$$

where:

U_{DAC} – the digital to analogical converter input voltage [V];

n – number of bits of the converter.

The block diagram of the position control system is presented in Fig. 6.

Starting from the control voltage of the velocity loop $U_c(s)$, obtained at the output of the analogical to digital converter:

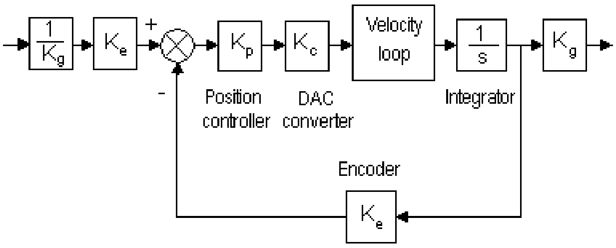

Fig. 6. The block diagram of the position control system.

$$U_c(s) = K_p K_c\left(\frac{K_e x_r(s)}{K_g} - \frac{K_e \omega(s)}{s}\right). \qquad (16)$$

where:

K_p – position controller proportional gain;

x_r – position reference (BLU).

It is now possible to determine the Laplace transform of the angular speed of the motor with regards of the position reference $x_r(s)$ and the static load $M_s(s)$.

Replacing relation (16) in (4), we obtain:

$$\omega(s) = \frac{s(K_0 x_r(s) - K_2 M_s(s))}{\tau s^2 + s + K}. \qquad (17)$$

where:

$$K_0 = \frac{K_1 K_p K_c K_e}{K_g} \quad \text{and} \quad K = K_1 K_p K_c K_e. \qquad (18)$$

The relation (17) indicates the fact that the closed position loop can be considered as a second order system with the characteristic equation:

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0. \qquad (19)$$

where the damping ratio and natural frequency are:

$$\xi = \frac{1}{2\sqrt{K\tau}}; \quad \omega_n = \sqrt{\frac{K}{\tau}}. \qquad (20)$$

The relation between natural frequency and the damping ratio is:

$$\omega_n = 2\xi K. \qquad (21)$$

Taking into consideration equation 20, the position controller gain Kp may be expressed as:

$$K_p = \frac{1}{4\xi^2 \tau K_c K_1 K_e}. \qquad (22)$$

4. COMPUTER SIMULATION

Based upon the model of the system, a simulation diagram was built for the position control system, using Matlab & Simulink software, as shown in Fig. 7. The velocity loop subsystem is presented in Fig. 8.

The CNC feed drive acts as a position control system, but with a numerical character.

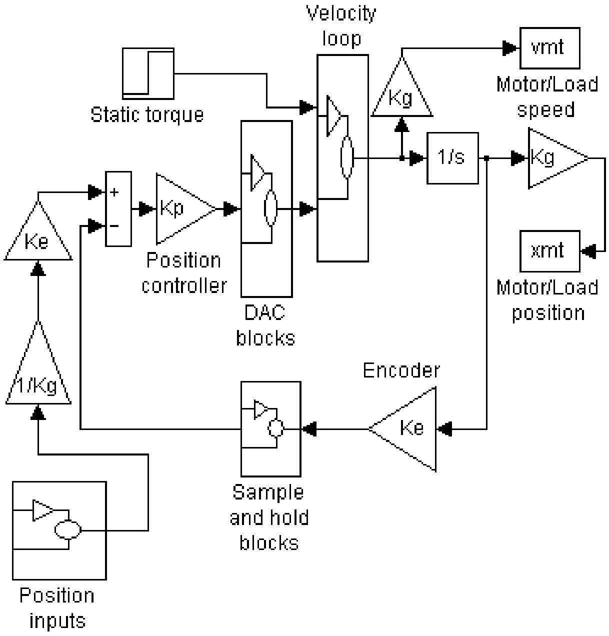

Fig. 7. The simulation diagram.

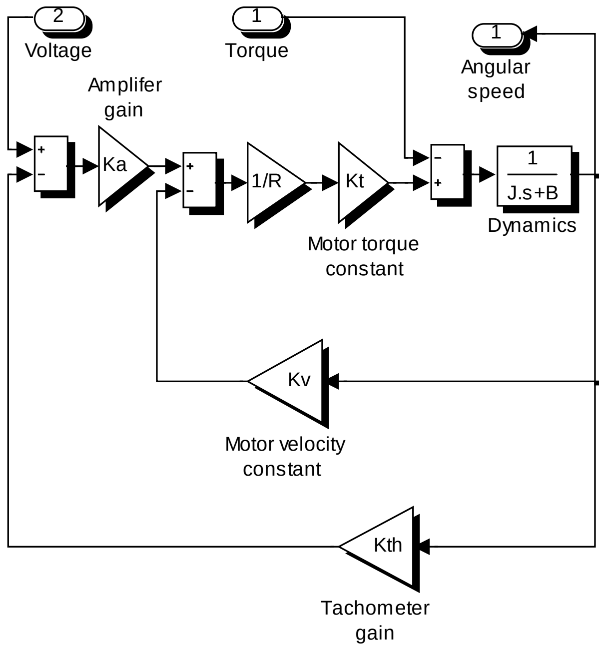

Fig. 8. The velocity loop subsystem.

In order to take that into consideration, two zero-order hold blocks were introduced in the model. One of these blocks was included in the digital to analogical converter (DAC) blocks and the other one on the position feedback loop, after the encoder, within the sample and hold blocks.

The zero-order hold has the following transfer function:

$$H_0 = \frac{1 - e^{-Ts}}{s}. \qquad (22)$$

where

T is the sampling period of the numerical system.

4.1. Input data

The input data the simulation was gathered taking into consideration the experimental system, a feed drives of a CNC milling machine. The position control systems, on all feed dives as actuation device on feed drives Sanyo T730-012 dc servomotors. The experimental parameters are synthesized in Table 1.

According to paragraph 3, the following parameters may be calculated: α = 0.3441, K_a = 7.8368, K_1 = 9.8181 rad/Vs. With a U_{DAC} = 8 V and n = 14, we obtain for the digital to analogical converter gain the value K_c = $9.7656 \cdot 10^{-4}$ V/bit.

Finally, imposing a damping ratio ξ = 0.707 and according to (15), a value K_p = 10.0821 is obtained for the position controller gain.

Table 1

Experimental parameters

Parameter	Unit	Value
Motor rated power *P*	[W]	300
Motor rated armature voltage *Ub*	[V]	75
Motor rated torque *M*	[Nm]	1.18
Motor rated rotating speed *n*	[min-1]	2 500
Motor instantaneous maximum armature current *i*	[A]	40
Motor armature winding resistance *R*	[Ω]	1.1
Motor torque constant *Kt*	[Nm/A]	0.273
Motor velocity constant *Kv*	[Vs/rad]	0.273
Motor instantaneous maximum angular acceleration *ε*	[rad/s2]	38 400
Motor rotor inertia *Jm*	[kgm2]	$0.270 \cdot 10^{-3}$
Mechanical time constant *τm*	[ms]	0.004
Electrical time constant *τe*	[ms]	0.0015
Load inertia *Jl*	[kgm2]	$2.583 \cdot 10^{-3}$
Motor viscous braking constant *Bm*	[Nms/rad]	$3.7242 \cdot 10^{-4}$
Tachometer gain *Kth*	[Vs/rad]	0.00668
Lead screw step	[mm]	5
Gear ratio *ig*	-	1
Incremental encoder gain *Ke*	[imp/rad]	2 500/2π
Mass of the slide	[kg]	30
Cutting force	[N]	1 000
Sampling period *T*	[s]	0.01

Figure 9 presents the simulated position output compared with the reference position input for the uncompensated system for a specific movement cycle. The system accelerates, then the machine slide travels with constant velocity, then it decelerates and the velocity changes its sign, following another acceleration-deceleration cycle but with reversed direction.

From Fig. 9 one may notice that a short delay between the axis stopping movement in one direction and starting movement in the other occurs, which causes the reversal spikes of the *X*-axis.

A fist approach in compensating this delay would be the increasing of the position controller gain K_p. However, a greater value of K_p will introduce a significant amount of oscillations in the system, so it has to be accompanied by another compensation method.

In order to reduce the oscillations, a derivative component *D* was introduced in the position controller, a component which is also allowed by the CNC controller. Initially, the derivative gain K_d of the position controller was kept to zero.

According to the documentation of the CNC controller, the derivative component *D* of the numerical position controller is defined by the following equation:

$$D = \frac{K_d(z-1)}{T_s z}, \tag{23}$$

where $z = e^{-Ts}$ is the discrete variable

Finding a proper value for the derivative gain K_p using an analytical process may be possible, but it is rather complicated.

A trial an error iterative simulation was used in order to find a set of appropriate values for both the increased proportional gain K_p and the derivative gain K_d of the numeric position controller.

After running the above mentioned process, an acceptable set of values were find as K_p = 25 and K_d = 0.1.

The simulated position output compared with the reference position input for the compensated system is presented in Fig. 10.

It is here noticeable the fact that the delay between the axis stopping movement in one direction and starting movement in the other is significantly reduced compared with the situation of the uncompensated system.

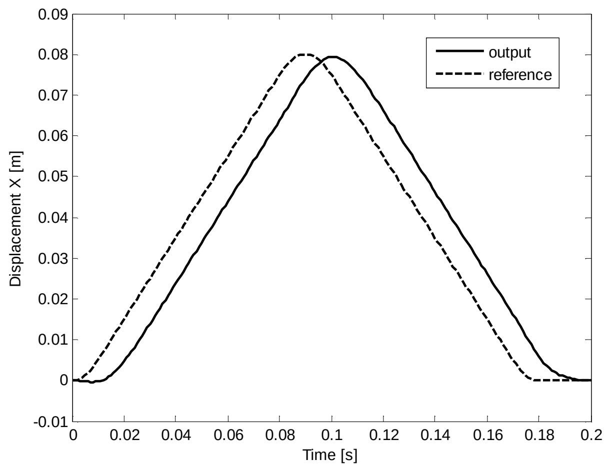

Fig. 9. Position output – uncompensated system.

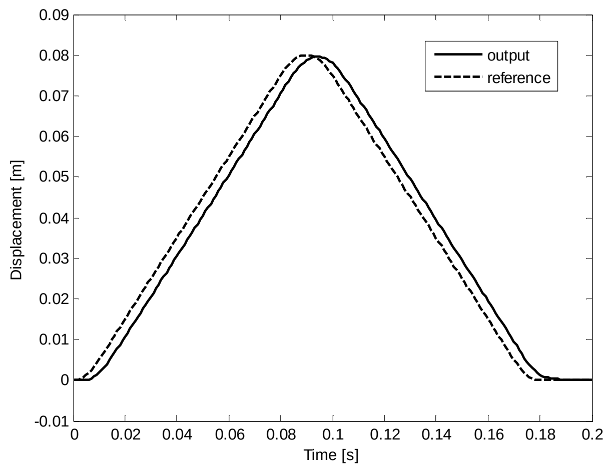

Fig. 10. Position output – uncompensated system.

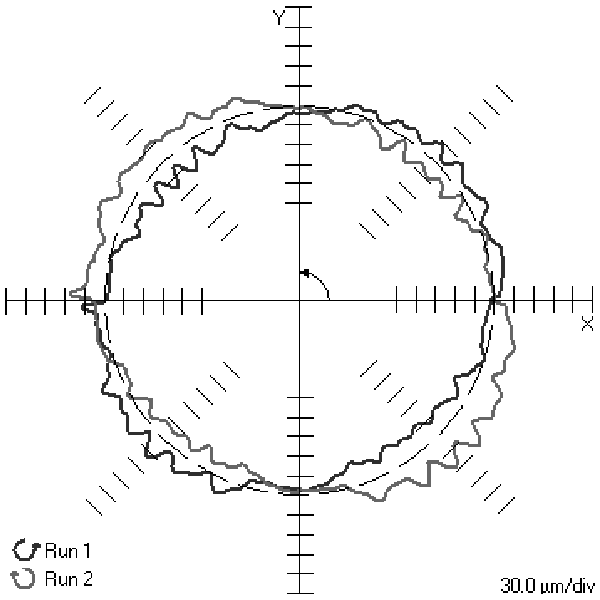

Fig. 11. The measurement after compensating the reversal spikes on *X*-axis.

After completing the simulation process, the compensation parameters were introduced in the experimental system and the circular test was run again.

The measurement result is presented in Fig. 11. One may notice the fact that the reversal spikes on *X* axis were reduced significantly, a fact which confirmed the proposed approach.

Thus, by a combined simulation and experimental process, the overall accuracy of the CNC machine was significantly improved. The process was performed entirely at the shop floor level, with low-costs involved and in a very short period of time.

5. CONCLUSIONS

This paper presents an approach for improving the contouring accuracy of a CNC machining centre.

The researcher in the field of CNC machine tools accuracy may find in the literature numerous such methods, but most of them have to be implemented in the designing phase of the machine, or require intervention in the CNC controller structure.

Both of the above-mentioned approaches are time consuming and cannot be applied at the shop floor level, which was the main goal of this research.

The proposed method is suitable to be implemented at shop floor level, which is very important in today's demanding production environment, where the manufacturers have to adjust rapidly the accuracy of their products, according to the customer's specifications.

The first stage of this approach involved a circular test, which revealed the most significant errors of the machine during a circular movement. Some of the errors were compensated either by mechanical adjustments of the feed axes or by using internal compensation algorithms implemented within the CNC controller.

However, a large amount of reversal spikes appeared on the *X* axis could not be compensated by these means.

In order to compensate the remaining errors, a logical approach would be to alter the control parameters of within the CNC controller.

It is well known that industrial CNC controllers offer a wide range of options regarding the control system parameters, which may be altered in order to obtain a better dynamic behaviour, and contouring accuracy of the machine.

However, the significance of these parameters and also the determination of some analytical relations to calculate an optimal value of them are hard to be found.

Moreover, complex mathematical models of the position control system on each axis are hard to be implemented, due to the difficulty to measure and/or calculate the parameters of such models.

The authors proposed a straight-forward mathematical model of a feed axis, based upon continuous transfer functions and presented a method for calculation of the model parameters. Also, the numerical character of the control system was taken into consideration by introducing specific transfer functions.

Based upon the proposed model, a trial and error simulation process was performed and a set of appropriate parameters were found. A new circular test validated the results of the simulation, showing that the remaining errors were reduced significantly.

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