

The G-code interpreter is installed on the first process computer, PC1, which controls the servo amplifier of the milling machine, the brakes of the servo motors and the spindle motor through parallel port, LPT2 / PC1.

The advance and sense signals are sent through the parallel port LPT2 / PC1 via the D0 and D1 data bits for the X axis, D2 and D3 data bits for Y axis and D4, D5 data bits for the Z axis.

To establish and control the spindle speed, a PWM signal is generated by software. This TTL signal is sent by the parallel port LPT2 / PC1 through data register D6 pin to an optocoupler and an RC circuit and converted into an analog positive electrical voltage in the 0 to 10 V range.

The second process computer, PC2, receives signals from the microphone to the sound card and from the digital ammeter to the serial port. These signals are processed by the optimization algorithm implemented in a Matlab application. The application sends through parallel port data register of the second computer process LPT1/PC2 via data pins D0, D1, D2, D3 TTL pulses to the status register pins S4, S5, S6, S7 of LPT1/PC1 parallel port on the first computer overwriting the spindle speed and feed rates with the new optimized values.

III. THE HARDWARE COMPONENTS OF THE EXPERIMENTAL STAND

The main hardware components of the experimental stand are: FUS 22 CNC milling machine, process computers, digital ammeter and the microphone. Also as auxiliary elements were designed and made the galvanic separation and signal conditioning circuits, DC 5 V DC sources for control logic, and DC 24 V sources for the brake actuators [9].

III.1 The selection of servo motors

Servo motors were selected in order to improve the initial performance of the milling machine. According to [8], the rotor's moment of inertia has to be greater than the overall moment of inertia of the axis that will be operated :

$$J_M = \frac{J}{C_m} \quad (1)$$

$$J = J_S + J_A + J_B \quad (2)$$

where:

J_M - moment of inertia of the servomotor's rotor

J - total moment of inertia of the axis

C_m - coefficient associated with the load and type of servo motor used

J_S - moment of inertia of elastic coupling between the servo motor and ball screw

J_A - moment of inertia of the decoder and the brake

J_B - the moment of inertia of the ball screw

We approximate the couplings and ball screws with a full cylinder and neglect the moment of inertia introduced by encoders and by the servo motor's brakes. For a full cylinder that rotates around the central axis the moment of inertia is:

$$J_C = \frac{m \cdot D^2}{8} \quad (3)$$

For the X and Y axes the moment of inertia are:

$$J_X = \frac{m_1 \cdot D_1^2}{8} + \frac{m_2 \cdot D_2^2}{8} \quad (4)$$

$$J_Y = \frac{m_3 \cdot D_3^2}{8} + \frac{m_4 \cdot D_4^2}{8} \quad (5)$$

where:

J_C - moment of inertia for a full cylinder

J_Y - total moment of inertia of Y axis

J_X - total moment of inertia of X axis

D - cylinder diameter

D_1 - ball screw diameter of X axis

D_2 - the diameter of the coupling on X axis

D_3 - ball screw diameter on the Y axis

D_4 - the diameter of the coupling on Y axis

m - mass

m_1 - mass of the X-axis ball screw

m_2 - mass of the coupling on X axis

m_3 - mass of the Y-axis ball screw

m_4 - mass of the coupling on Y axis

The Z axis was realized with two gear wheels and moment of inertia become:

$$J_Z = \frac{m_5 \cdot D_5^2}{8} + \frac{m_6 \cdot D_6^2}{8} + \frac{m_7 \cdot D_7^2}{8} \quad (6)$$

where:

J_Z - total moment of inertia of Z axis

D_5 - diameter of the gear wheel attached to the ball screw

D_6 - ball screw diameter

D_7 - diameter of the gear wheel attached to the servo motor

m_5 - mass of the gear wheel attached to the ball screw

m_6 - mass of the ball screw

m_7 - mass of the gear wheel attached to the servo motor

The calculated moments of inertia for the kinematics axes are shown in Table 1.

Table1. Moments of inertia of the kinematic axes

$J_x(\text{Kg.m}^2)$	$J_y(\text{Kg.m}^2)$	$J_z(\text{Kg.m}^2)$
0,0000784	0,0000705	0,000224

On each kinematic axis the servo motor's moment of inertia must be at least equal to the values previously calculated. These conditions are met by the three phase brushless Glentek servo motor GMB 4525-55 - N - 12144107 type. Servomotor nominal power is 1.6 kW, the rated rotation speed is 3000 RPM, the operation torque is 6.2 Nm and the moment of inertia is 0.000294kg.m².

The main electrical characteristics of brushless Glentek servo motor GMB 4525-55 - N - 12144107 are: the constant voltage of 55 V / 1000 RPM, nominal electric intensity is 8.9 A and the maximum electrical voltage is 350 V.

Glentek servo motors have been provided with optical encoders. The optical disk of each encoder has 4096 circumferential lines and differential output signal. At each complete rotation of the rotor, the output signal consists of 16,384 pulses. Considering the 5 mm ball screw pitch, the theoretical resolution of each axis will be 0.000305 mm. This value can't be practically achieved.

III.2 The selection of servo amplifiers

The servo amplifiers must be able to provide the necessary power that the engines require.

In order to control the CNC milling machine using STEP and DIRECTION signals from EMC2 software, the chip firmware in the servo amplifier was programmed so it can work in PULSE FOLLOWER mode.

We used three servo amplifiers of the same type, SMC 9715-4A-3 with associated power supplies. The supply voltage for the servo

motors has to be in the range of 190 - 370 V DC and the supply voltage for the logic circuits is 5 V DC. The nominal intensity of electric current in servo motors is 15 A and the maximum intensity of transient supported peak power is 30 A.

During acceleration, the GMB 4525-55 servo motor can absorb a maximum electrical intensity of 26.6 A, so this do not overwhelm the servo amplifier. The setting up of the servo amplifiers and the monitoring of the servo motors was made using the dedicated software, Glentek-Motion Maestro.

III.3 The selection of the spindle motor

In order to adjust the spindle speed in real time regarding to the current work conditions and milling process was necessary to use an electric motor that allow continuous change of its rotational speed. For the spindle was chosen a Leroy Sommer electrical motor. The engine was connected directly to the main shaft using a flexible coupling. The main features of this motor are: 550W electrical power, 475W mechanical power at the shaft and a maximum rotational speed of 1500 RPM. In order to change the rotational speed during milling process, the engine was equipped with an electronic Varmeca controller which requires an analog input voltage in the 0 - 10 V range.

III.4 Process computers

The process computers are two identical IBM PC AT compatible computers equipped with Intel Core 2 Duo E8400 microprocessor, 2 GB RAM and 160 GB SATA HDD. Each computer is fitted with one extension card of SW 1163 type entered into a PCI slot. The SW 1163 card has two parallel ports at 0x278 and 0x378 addresses, working with TTL-level electrical signals. Additional, the second process computer is equipped with a sound card Creative Sound Blaster type.

III.5 The measuring microphone

For precise recording of the sound emitted during milling process at the cutter - work piece level, was used an electret type microphone constructed with a Panasonic WM 61 capsule. The linearity of the microphone in the

frequency range of interest, 20 to 15.000 Hz is 3 dB.

III.4 The digital ammeter

The digital ammeter used in the experiments was a Mastek 345 model. This ammeter allows communication with an IBM PC AT computer through the serial port at a speed of 2600 baud [10].

IV. THE SOFTWARE COMPONENTS OF EXPERIMENTAL STAND

The software component of the experimental stand consists of operating systems on process computers, the G-code interpreter and an application written in Matlab 6.5.

IV.1. The G-code interpreter

The software that controls CNC milling machines must be able to send coherent commands in time without information loss. We installed on the first process computer, PC1, the Linux - Ubuntu 6.0.1 operating system [2] along with RTAI [5], [7] components which provide capabilities for working in real time.

The installed G-Code interpreter is the EMC2.1.0 version of the Linux Enhanced Machine Control EMC2, EMC [1]. Instructions that allow overwriting current feed rate and spindle speed values read from the NC file with new optimized values are M50 and M51.

IV.2 The MATLAB application

On the second process computer PC2, were installed a Windows XP SP2 operating system and the MATLAB 6.5 software.

We wrote a Matlab application called TESTCNC in which is implemented the optimization algorithm. This application contains also a simple user text interface, an input subroutine for reading the serial port INPUT_Serial, an input subroutine for reading the microphone signal INPUT_MIKE, an output subroutine for sending the optimized values to the PC1 process computer OUTPUT_Paralel and a subroutine for saving all the data to a file, WRITE_Data_File.

The first input data set in TESTCNC program are the initial spindle speed, the initial feed rate and the prerecorded value of the

acoustic intensity obtained in a milling process with those values. The second input data set is the acoustic intensity in the current milling process picked up in real time by the microphone through the sound card and the electrical intensity taken by digital ammeter over the serial port RS 232/PC2.

The output data delivered by the TESTCNC program are the TTL pulses through data register of parallel port D0, D1, D2, D3 LPT1/PC2 applied to the LPT1/PC1 in order to modify the feed rate and spindle speed.

V. TUNNING AND TESTING THE EXPERIMENTAL STAND

Checking the experimental stand involved the interconnection of all components so that they can work as a whole mechanism.

V.1. Adjusting the servo amplifiers

Adjusting the servo amplifiers installed on CNC milling machines determines the stability of the axis movement and finally the milling process. Methods for servo amplifiers adjusting are presented in [8], [6], and [4].

Because the numerical axes have not identical load, each Glentek servo amplifier must be adjusted separately. The servo amplifier has one PID controller for speed closed loop, one PID controller for position closed loop and one PI controller for the current intensity closed loop. The general form of a PID controller of $f(t)$ function and $u(t)$ output function is:

$$u(t) = C_p \cdot f(t) + C_i \cdot \int f(t) dt + C_d \cdot \frac{df(t)}{dt} \quad (9)$$

where:

C_p - proportional coefficient

C_i - integrative coefficient

C_d - derivative coefficient

These coefficients determine how the controller will respond to the external disturbances, in an attempt to maintain the output function between defined limits. The coefficients are determined studying the system response to known disturbance.

The controller is unstable if the value of the output function oscillates around the set point to be achieved or increases exponentially.

The manual adjustment of the controller is often empirical. The SMC 9715-4A-3 servo amplifiers are tuned using a digital oscilloscope implemented in the Glentek Motion Maestro software.

After determining the coefficients of the PID regulators, they are stored in the EEPROM memory of servo amplifier. The current values of the PID coefficients determined for the combination FUS 22 CNC milling machine and GMB 4525-55 servo motors are listed in Table 2. They are calculated relative to the internal representation of data in the DSP that equipped the servo amplifier and have no direct physical significance.

Table 2. PID regulator coefficients

Servo axis	C _{PV}	C _{IV}	C _{DV}	C _{PP}	C _{IP}	C _{DP}
X	32767	1	12340	187	0	32
Y	32767	1	11700	183	0	32
Z	32767	1	10450	179	0	32

V.2 Verification of the experimental CNC stand

Verification of the experimental CNC stand was made over several experiments. In the first set of experiments were monitored and recorded the acoustic emissions at the cutter - work piece level and the intensity of electric current in the controller of the spindle motor.

Starting from the data obtained in the first set of experiments experiment we conclude that we can modify the spindle speed down to 80% of the initial value and the feed rate up to 130% of the initial value. These hypotheses were tested in a second set of experiments.

The experiments consisted in milling straight channels in OL52 steel using the Kennametal cutters. The initial feed rate and cutting speed was determined as specified in the Kennametal catalog [3] correlated with the initial wear factor of cutters.

The NC programs that were used in the experiments have the following form:

```
N30 G21
N40 G90
N50 M50 P1 / Activate the feed rate override
N60 M51 P1 / Activate the spindle speed
override
```

```
N70 M3 S1000
N80 G01 F200 Z-5
N85 G01 F600 X0 Y0
N90 G01 F20Z1 G4P1
N100 G01 F70 X100 Y0
N110 G01 F200 Z-5
N110 G01 F600 X0 Y0
N120 M2
```

The sequence of TESTCNC.m MATLAB program used to estimate the acoustic intensity and the intensity of the electric current in the spindle motor controller has the form:

```
030 %
032 Fs = 8e3;%
034 responseType = 'fast';
036 C = 90;
038 clc;
040[AI,Fs,N]=
initSoundCard(Fs,responseType);
042 % Read sound card data ;
044 x = getdata(AI);
046 % Estimate the sound intensity
050[X,dBA1,dBA2,F1,F2]=
estimateLevel(x,Fs,C);
078 % Open a text file for writing data .;
080 fid = fopen('F1D6S1200','a');
082 % Initiate a timer.;
084 002 t = clock;
086 for i=1:2400;
088 % Continuously read the sound intensity.
090 x = peekdata(AI,AI.SamplesPerTrigger);
094 [X,dBA1,dBA2,F1,F2] =
estimateLevel(x,AI.SampleRate,C);
096 % Read digital ammeter on the serial port,
098 fprintf(ser1,'ATI8');
100 val= fscanf(ser1);
102 val2=val(5:9);
```

VI. CONCLUSIONS

The CNC experimental stand that was designed and made allowed the monitoring and recording of the acoustic emission and electric current intensity in the spindle motor controller in real time during the milling operation. In the second set of experiments we intended a small response time 10 to 50 ms, of the milling machine due to the changing intensity of electric current or acoustic emission intensity. Because of the large inertia of the numerical

axes the response time was increased up to 560 ms. We can conclude that a low response time leads to higher accelerations and large inertial forces that can damage the cutting tools and alter the precision of ball screws.

The feed rate and cutting speed could be changed in the proposed limits. The spindle speed was continuously decreased down to 80% of the initial value and the feed rate was increased up to 130% of the initial value in 2% steps with latency imposed by the dynamic behavior and inertia of the FUS 22 CNC milling machine. All the data, spindle speed, feed rate, the intensity of acoustic emissions at the cutter - work piece level and the intensity of electric current in the controller of the spindle motor was recorded and saved in text format files for analysis.

In a future research, we intend to replace the PC2 process computer with a microcontroller on which will be implemented a genetic real-time closed loop optimization algorithm, based on the saved experimental data.

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Proiectarea și executarea unui stand experimental CNC pentru monitorizarea și modificarea în timp real a parametrilor de frezare

Rezumat: În acest articol este prezentată pe scurt proiectarea și execuția unui stand experimental CNC pentru monitorizarea operației de frezare. Standul experimental trebuie să funcționeze asemenea unei mașini de frezat cu comandă numerică și să înregistreze emisiile acustice care apar în timpul frezării și intensitatea curentului electric prin controlerul motorului arborelui principal. Conform acestor date, standul experimental trebuie să permită suprascriserea vitezei de avans și a vitezei de așchiere preluate inițial din fișierul NC cu valori noi modificate.

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