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The CNC Machining Process with Multiprocessor Control

Traditionally, machine tool with CNC works employing a hard program system (system that works under beforehand determined program). However, in reality the instability involved in machining process is closely connected with the workpiece configuration, the working trajectory, condition of the working tool and a type of material to be machining. In this work a method of a CNC machine as a multiprocessor system is proposed. It involves a few steps focused on increasing productivity of the machining process and keeping the surface quality requirements of the finished piece. For the validation of the method, a multiprocessor system was selected, basically consisting on a CNC high speed milling machine processor, supplied with accelerometers connected to a Standard PC-acquisition system processor. Experimentally, it is shown how it is possible to find the optimal machining characteristics and to be into an adaptive control regime, which prevents the appearance of vibrations by clarify the working region on-line and supporting the relationship between quality and productivity, according to technical requirements.

Introduction

In a competitive market, increasing productivity means increasing the average profit rate for the industry. Looking closely at the high speed machine tool industry, high productivity is connected to the optimization of two important variables, speed and feed up to the point of minimizing returns. Changing those variables, the obtained output is only beneficial if the end result can be summarize as good parts, minimum rework and near-zero scrap.

The instability typical for machining operations is the limiting factor for most of the optimization methods. Chatter is a problem of instability in the metal cutting process, characterized by violent vibrations, loud noise and poor surface quality of the finished piece. This instability phenomenon has been affecting the manufacturing community reducing the tool life and the productivity of the machining process, by interfering with the normal function of the machine [1].

The regenerative effect has become the most commonly accepted explanation for machine tool chatter, this effect is related to the cutting force variation due to the wavy workpiece surface cut during the previous revolution [2].

In milling process, both theoretical and prediction models of regeneration to explain chatter instability, are more complex than those related to the turning process. The regenerative effect due to the chip thickness variation is illustrated on Fig. 1. While machining, the cutting tool may face a hard spot on the surface of the workpiece and some vibrations are triggered. This leaves behind a specific wavy surface on the workpiece, as shown in the figure. When a subsequent pass is being made, the cutter removes material from an existing wavy surface and at the same time leaves behind a new wavy surface.

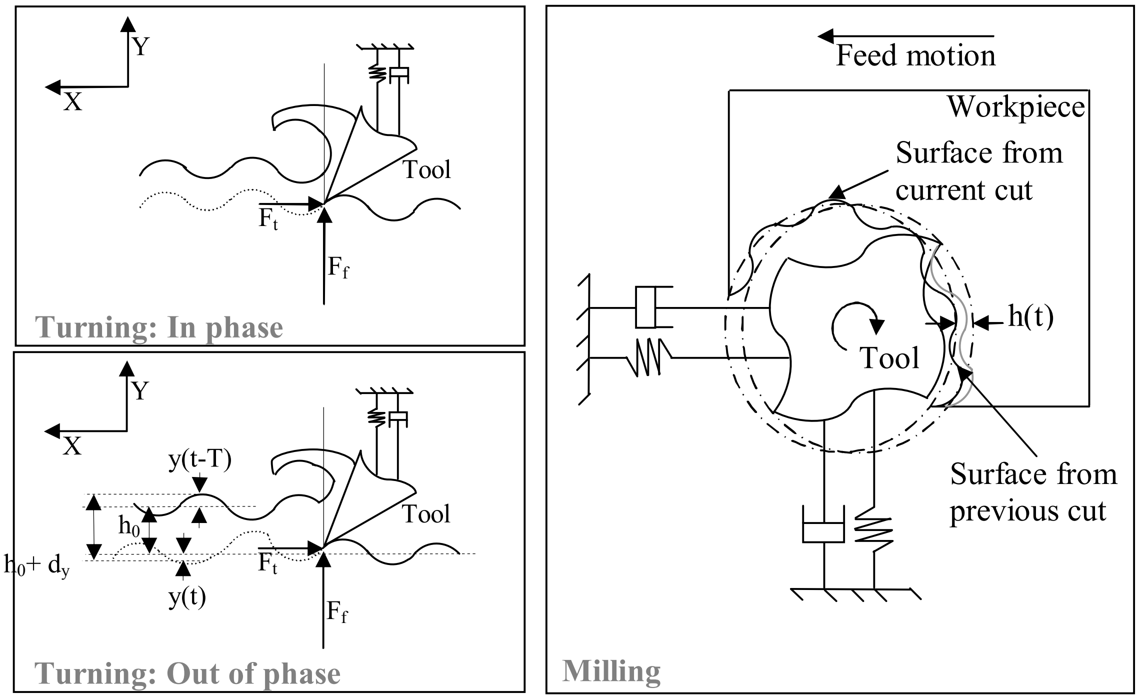

Figure 1 – The regeneration process

The chip that is produced by this cut carries both, the waviness from the previous pass and that translated over by the current pass. If the new cut leads to a chip with variable thickness (i.e. waves are out of phase), this would produce variable forces on the cutting edge and eventually, a vibration. If the waviness of the chip is in phase, it produces a stable cut [3]. This is the process of regeneration.

Objectives

The main purpose of this work is to show how to change CNC machine tool with a hard program system (system that works under beforehand determined program) into an adaptive program system with the help of an additional processor connected to the CNC processor.

Besides, it is intended to show the possibility of performing a high productivity machining process, obtaining better surface quality, increasing the metal removal rate and minimizing costs with a CNC adaptive working process.

Description of the problem

The loss of dynamic stability (chatter) limits the metal removal rate in high-speed machining operations, arising from two primary sources: (1) regenerative instabilities that result from the overcutting of previously cut surface; and (2) the instability involved in the machining operations [4].

Traditionally, machine tool with CNC works employing a hard program. However, in reality the instability involved in machining process is closely connected to the work piece configuration, the working trajectory, condition of the cutting tool and a type of material to be machining.

Commonly, to avoid chatter and to respect the piece surface quality requirements, industry workers prefer to decrease productivity.

A well known solution to detect chatter is realized in Harmonizer®, an industrial product of *Manufacturing Laboratories, Inc.* [5], which uses acoustic emission techniques. Harmonizer® gives a possibility to stop the process manually, when chatter appears, though it is sensitive to the external noise (for example, when more than one machine are working close together). Unfortunately, Harmonizer® doesn’t include mechanisms to change a program automatically, to provide a flexible control for CNC machines.

To prevent productivity losses it is necessary to create a special program of adaptive control, because with non-flexible control it is impossible to adjust the process parameters to the real conditions of the working process.

Mechanical model

The following mechanical model has its bases on the paper [1] by A. Ganguli, et al.

Referring to the Fig. 1, assuming the cutting tool to be flexible only in the Y-direction, the uncut chip thickness $h(t)$ at any instant is given by

$$h(t) = h_0 + y(t-T) - y, \tag{1}$$

where y and $y(t-T)$ are also called in the inner modulation respectively. Assuming that the cutting forces are proportional to the frontal area of the chip, the cutting force in the Y direction is:

$$F_c(t) = K_f a\left[h_0 + y(t-T) - y\right]. \tag{2}$$

Many authors [6-8] have observed the existence of damping in the cutting process, the variable of displacement and its derivative in the cutting force relationship was incorporated. Through those studies some experimental investigations have shown the dependence between the cutting force and the cutting velocity, the rake angle of the cutting tool and the feed [9]. Others [10-13] have dealed with non-linearities such as the cutting tool leaving the workpiece, due to excessive vibrations, and relating cutting forces to the power of the chip thickness. The dynamic equation of motion in the Y direction is

$$m\ddot{y} + c\dot{y} + ky = K_f a\left[h_0 + y(t-T) - y\right]. \tag{3}$$

Equ. 3 is a Delay Differential equation. In Laplace domain $y(t-T) = y(s)e^{-sT}$. Then, defining the machine tool transfer function between the cutting force F_c and displacement y as $G(s)$ and substituting for y_0, it is obtained in Laplace domain,

$$\frac{h(s)}{h_0(s)} = \frac{1}{1 + K_f a G(s)\left(1 - e^{-sT}\right)}, \tag{4}$$

where

$$G(s) = \frac{y(s)}{F_c(s)} = \frac{1}{ms^2 + cs + k}. \tag{5}$$

Therefore the characteristic equation of the closed loop system is

$$1 + K_{cut} G(s)\left(1 - e^{-sT}\right) = 0, \tag{6}$$

where K_{cut} is the product of K_f and a. This equation is not restricted to a single degree of freedom (SDOF) oscillator but can also be extended to single input single output (SISO) systems with multiple degrees of freedom, when the appropriate expression for $G(s)$ is used. Then a close loop feedback diagram for regenerative chatter was introduced [14], it is shown on Fig. 2 [1].

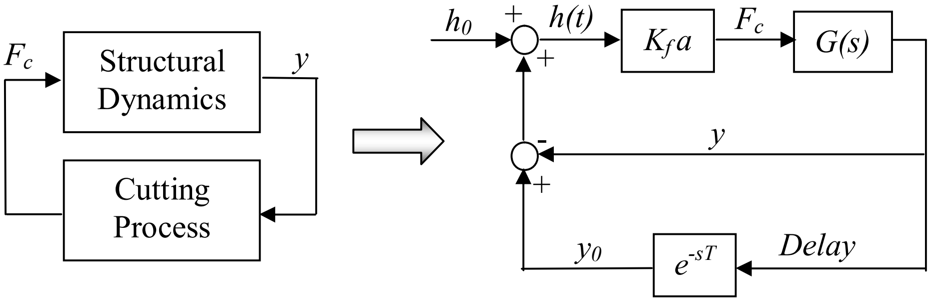

Figure 2 – Closed-loop representation of chatter

Under certain combinations of K_{cut} and spindle speed N, the feedback loop becomes unstable, leading to chatter. The traditional method of stability analysis assumes that a root of the characteristic equation is on the imaginary axis, i.e., $s = \pm j\omega_c$, where ω_c is the chatter frequency and then solves for the corresponding limiting value K_{cut} and spindle speed N. Based on this, the classical stability lobe diagram was introduced [15], it is a plot of K_{cut} or a versus N. Some authors [14], [16], [17] formulate limiting width of cut a_{lim} as a function of the frequency response function G(s), others [18] use the Nyquist Criterion for stability analysis.

Machine tool description

This paper has been focused on a CNC milling machine tool, but the concept can be used on any CNC machine tool (i.e. milling machine, lathe machine, drilling machine, high speed machining center, etc.).

So, a CNC milling machine tool is considered. It is able to execute a machining operation on a workpiece with a help of a rotating cutting tool. On this machine, cutting tool is connected to a rotating spindle, which can make vertical and horizontal progressive movements. Working piece is fixed on a special table, which can also make progressive displacements. So, the considered machine is able to move workpiece and cutting tool realizing their relative progressive displacement. The movement is executed with the help of motors under the control of a previously CNC prepared control program, which determines the trajectory to be followed and the velocity of the relative movement of workpiece and cutting tool.

Additional equipment description

The additional equipment consists of an electronic device constructed of:

– one sensor or a group of them for measurement of the variables of the machining process. Variables of the machining process are quantities, which are fully described by a magnitude alone (i.e. distance, acceleration);

- a standard PC with a data acquisition system to register the variables and to calculate and register the properties of the machining process. The process is characterized by the values of displacement, deformation of the cutting tool, deformation of the workpiece, amplitude and frequency of vibration, etc., which define the properties of the process.

The standard PC and the acquisition system have a two-side connection with the sensor or the sensors for measuring the variables of the process. Besides, PC has also a two-side connection with the machine tool CNC.

Because of the established connection between all the elements it is possible to make an automatic change of one or more than one of the machining process parameters online.

Control method of a CNC multiprocessor machine

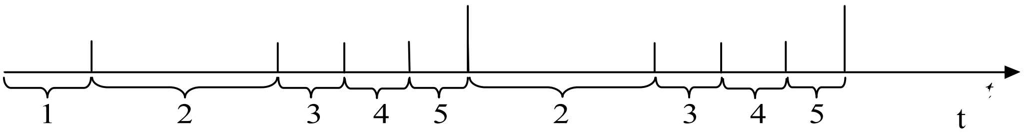

Figure 3 – Control method of a CNC machine as a multiprocessor system

As it is shown on Fig. 3, the considered method [19], [20] can be summarized as follows:

1. First, the method presupposes some waiting time for process stabilization.
2. The variables of the machining process are measured and recorded, at least, on a part of the working trajectory.
3. The properties of the machining process are calculated and registered, at least, on a part of the working trajectory.
4. The comparison of the measured properties of the machining process and some previously defined values is made.
5. Finally, the results of the comparison are used for a decision making. If the measured values of the machining process are between some previously defined limit values, the machining operation is continuously executed without any change. If the measured values are bigger than the upper of the pre-established limit values, the velocity of each motor for the progressive movement of the cutting tool and the workpiece are automatically decreased in the equal percent. This allows conserving a beforehand given trajectory of the process, changing, at the same time, parameters of this process. If the measured values of the machining process are less than the lowest pre-established limit value, it is necessary to increase the velocity of each progressive movement motor in the equal percent. The spindle speed value would be conserved in any case. This step exposes a simplest way for making a decision, however, the method could be improved by adding a PID controller in this step.

The first step is required once, just at the beginning of the machining process, the following four steps are repeated up to the process is completed.

Experiments

For the validation of the method, a multiprocessor system was selected. Fig. 4 describes the experimental set-up. As it is illustrated on the figure, the experiments were performed in a test multiprocessor system, basically consisting on a CNC high speed milling machine processor and a Standard PC-acquisition system processor.

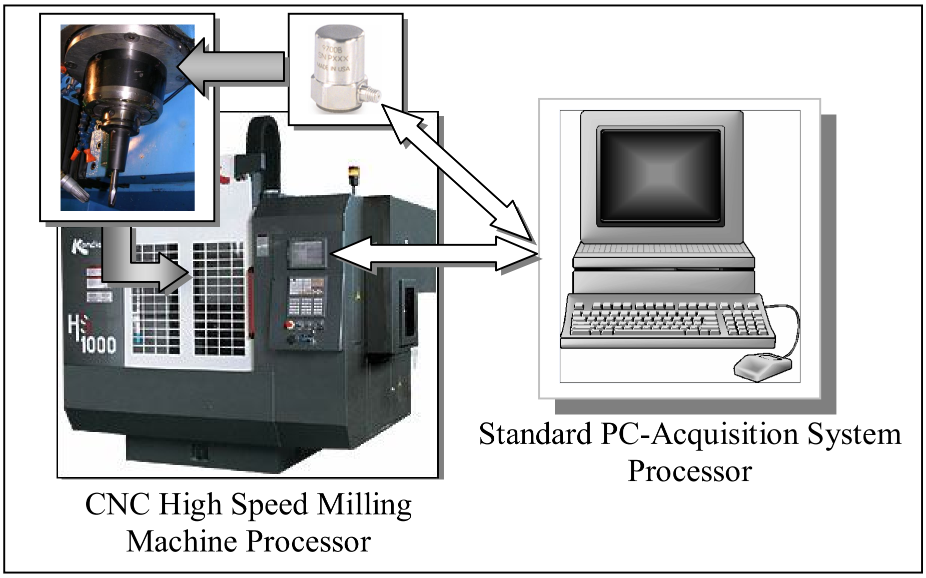

Figure 4 – Machine tool multiprocessor system: experimental set up

The cutting tests were conducted on a *Kondia HS1000* CNC high speed milling machine. It is a portal bridge-type vertical machining centre with open CNC architecture (Siemens SINUMERIK 840D). This high speed CNC machine tool is able to achieve a spindle speed of 24000 rpm and a cutting feed rate of 12 m/min. Its working table is able to execute progressive displacements along the Z and X axis, its spindle head is able to execute a progressive displacement along the Y axis. Due to the relative movement, the machining center is able to make travels up to 1000 mm along the X axis, 600mm along the Y axis and 510mm along the Z axis. The machine's spindle power is 17,5 KW.

Three accelerometers, each of them positioned on one of the three coordinate axis system (Brüel & Kjaer, model 4371 for X and Y axis and model 4370 for Z axis). The accelerometers are installed into an aluminum ring, and fixed on the spindle head of the machine tool (Fig. 4)

Besides the accelerometers, a standard PC and a four–channel card *IOtech DBK17* data acquisition system are part of the additional equipment, forming the standard PC-acquisition system processor.

For this experimental set up, a friendly *LabVIEW* based interface platform was specially designed, it establishes communication in each moment between the standard PC–acquisition system processor, the CNC high speed milling machine processor and the accelerometers sensors in each moment, supporting a two-side connection between both processors any time.

Once established the experimental set up, one first milling test was design in order to support the control method and establishing some initial limit values. The milling test consists in machining a series of grooves with a constant spindle speed of 12000 rpm and a feed rate of

0,07 mm per teeth, on a 180x105x25 mm 114 steel piece with hardness of 175 Hb and traction resistance of 600 N/mm^2. The axial cutting depth for each groove started at 0,4 mm and it was increased in steps of 0,1 mm up to find clear signs of chatter (Fig. 5).

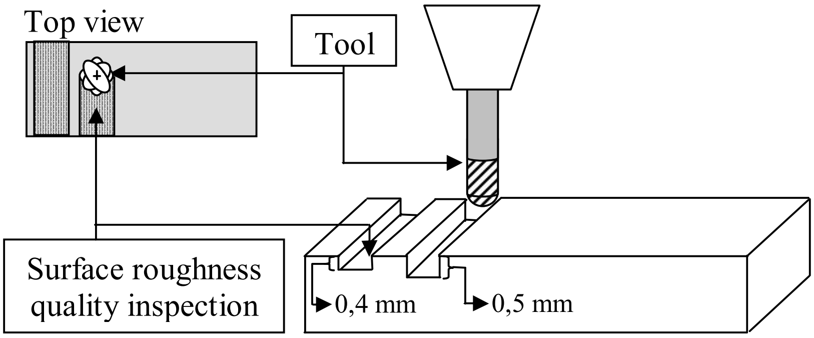

Figure 5 – Experimental milling test

For the milling test, a two cutting edges tool *Karnash 30.6472* with 10mm of diameter was installed into a balanced thermal *Kelch HSK 60X10X85* tool holder. The cutting tool is 90 mm long and presents a straight shank and drive flat to DIN 6535 HA 25°. Both elements are connected to the spindle head through the thermal tool holder.

Once the preliminary milling test was finished each cut passing was inspected for surface roughness quality (Fig. 5), and the obtained data were correlated with the measured values of acceleration. Fig. 6 shows the results obtained at the end of the experimental test. It is clear that Z axis accelerometer curve has a close relationship with the roughness surface quality curve. Unstable (chatter) milling processes were all those over 0,8 mm of depth of cut.

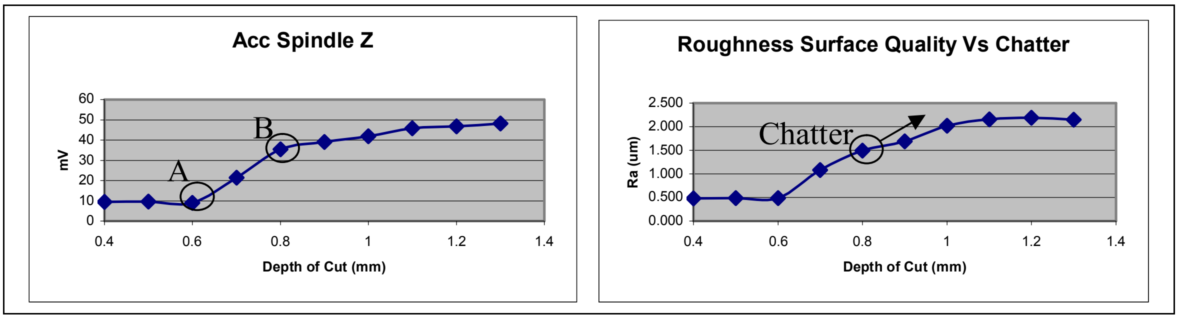

Figure 6 – Experimental results

Based on the preliminary results and the proposed experimental set up, once the upper and lower limits are established, it is possible to employ the proposed method. Fig. 7 shows the diagram of control for the machine tool as a multiprocessor system, the figure represents in a detailed way how the described above method is working.

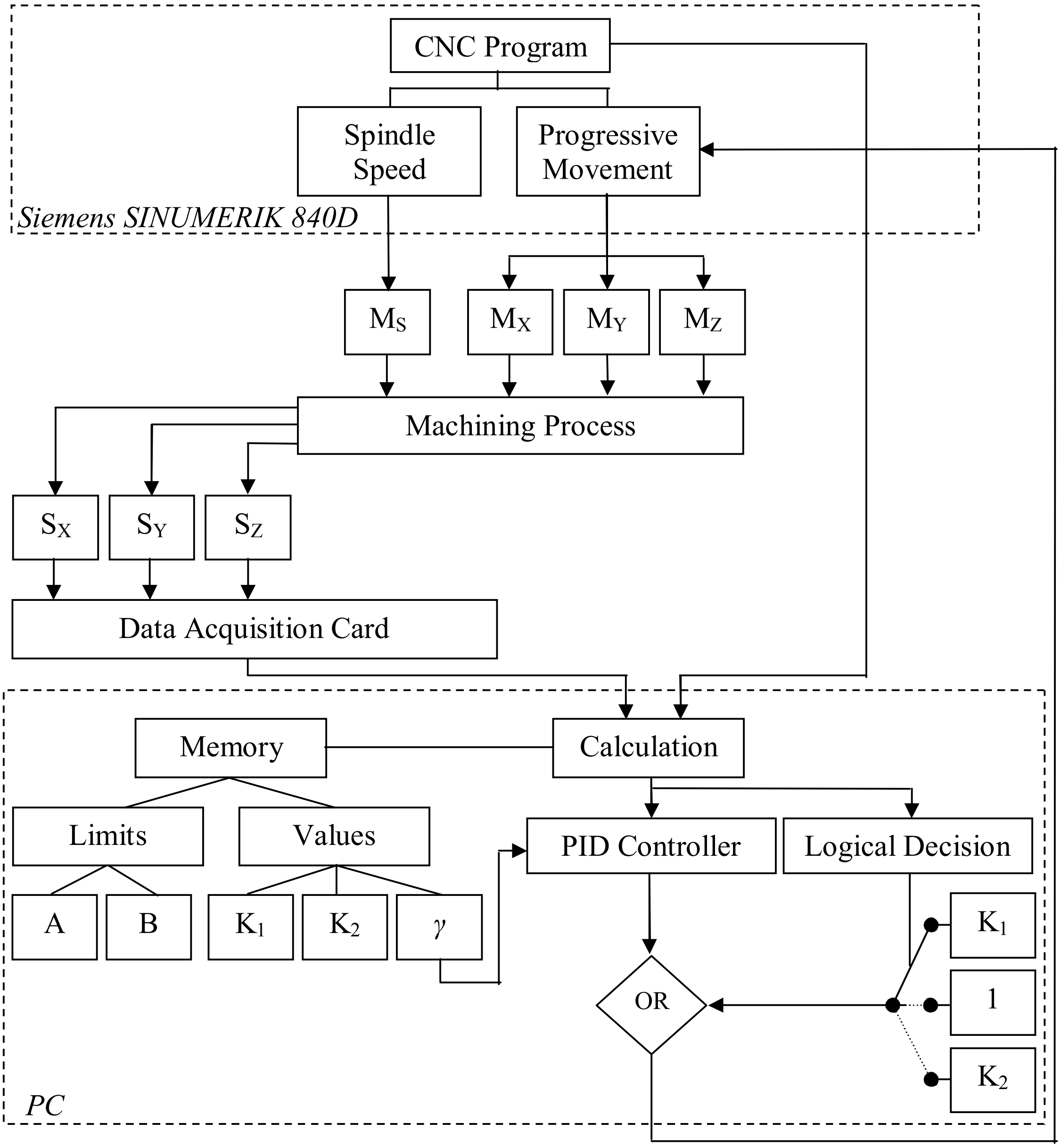

Figure 7 – Diagram of control for machine tool as a multiprocessor system

The SINUMERIK 840D is a system platform with progressive functions for the high speed machine tool technology, offering a high degree of performance and flexibility for this multi-axis system. It contains two Intel Pentium® processors. One digital signal processor per axis controls directly with high precision the rotary (driven along a circular path) and linear (driven along a straight path) axis drive motors (M_S, M_X, M_Y, M_Z).

Once the cutting tool is precisely and automatically positioned according to the piece specifications, the CNC program will be executed by giving a set of step by step instructions to the motors. At this moment the machining process has started, the workpiece may be milled to a combination of shapes according to the specifications.

As it is represented in the above diagram, the group of sensors (S_X, S_Y, S_Z), an accelerometer per linear axis, are monitoring the machining process. The *IOtech DBK17* four-channel simultaneous sample and hold card is acquiring and amplifying the signal, then, automatically those values are recorded into the PC for calculation. According to the control method, at this point, the variables of the machining process (acceleration signals) are measured and recorded, at least, on a part of the working trajectory.

The PC through its central processing unit supports a *LabVIEW* based interface platform for all the calculus, memory, decision and comparison activities. Helped by the *NCDDE* server (ncdde.exe), which is part of the *SINUMERIK* software, a communication protocol is established, being possible to work under a client/server application between the CNC high speed milling processor and the PC-acquisition system processor at any time.

Once the vibration acceleration signals coming from the sensors are measured and recorded, the acceleration of the cutting tool is calculated and registered on the working trajectory.

Based on the limits and values the interface platform is able to formulate an action to be followed by the digital signal processor that controls the linear axis drive motors. The action is based on a PID controller or a logical decision scheme, according to the working mode chosen by the operator.

According to the preliminary milling test, limits are (Fig. 6):

$$A = 9mV, B = 35mV, \tag{7}$$

where A represents the lower limit and B the upper limit. From other side, the values K_1 and K_2 are manually introduced to the system, and they are determined according to the operator's experience. For example, in this paper the values of K_1 and K_2 have been proposed as:

$$K_1 = 0{,}15, K_2 = 0{,}15. \tag{8}$$

In case the system is working under the logical decision mode, the properties of the machining process, acceleration of the cutting tool, are compared to the limits and values already recorded in memory. Focusing on this preliminary milling test, the lower limit is established at 9 mV (A) and the upper limit at 35 mV (B), the K_1 and K_2 values are established at 15 %. If the measured values of the machining process are between 9 and 35 mV, the machining operation is continuously executed without any change, it means in this case the actual feed rate is multiplied by one, conserving the same value. If the measured values are bigger than 35 mV, the feed rate is automatically decreased in 15 %, it means, the new feed rate value is,

$$\textit{New feed rate value} = \textit{Actual feed rate} * (1 - K_2). \tag{9}$$

This allows conserving a beforehand given trajectory of the process, changing, at the same time, parameters of this process. If the measured values of the machining process are less than 9 mV, it is necessary to increase the velocity of each progressive movement motor in the equal percentage (15 %), it means, the new feed rate value is,

$$\textit{New feed rate value} = \textit{Actual feed rate} * (1 + K_1). \tag{10}$$

The spindle speed value would be conserved in any case.

In case the system is working under the PID controller mode, the controller would define the relationship between changes in the measured variables of the process and changes in the controller output. In this case, the new feed rate value would always try to preserve a γ value during the machining process, as follows,

$$\gamma = \frac{\Pr oductivity}{Quality} = \frac{B - C}{B - A} * 100\ \% \tag{11}$$

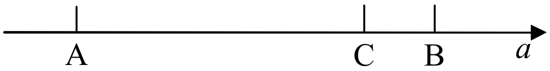

Figure 8 – Limiting values of acceleration (A and B) and a value C that determines a relation between productivity and quality

Fig. 8 and Equ. 11, represent the relationship that γ establishes between productivity and finished surface quality. The γ value is manually introduced to the system by the operator. In the process of choosing γ it is important to take into consideration when $\gamma \to 0$ the machining process will be executed trying to achieve the maximum productivity and in consequence the minimal surface quality standard. In case $\gamma \to 1$, the machining process would experiment an inverse situation, the process would be executed achieving the maximums surface quality standards with minimum of productivity.

As it is supported by the preliminary results (see Fig. 6) unstable (chatter) milling processes were reflected by Ra coefficients over 1,5 μm. In this case, as it is illustrated in Fig. 8, if the C value is closer to the B limit than to the A limit, the output feed rate value would keep a close relationship to the productivity factor, decreasing the surface quality of the finished piece. If the C value is closer to the A limit than to the B limit, the output feed rate value would keep a close relationship to the surface quality of the finished piece, decreasing productivity of the machining process.

Because of the nature of the control method, the CNC high speed milling processor is always sending data about other variables and parameters of the machining process which can not be measured by the established group of sensors to the PC-acquisition system processor (i.e load, feed, torque, etc, etc, etc.).The feedback is always guaranteed, supporting a closed-loop system. This guaranteed two side connection between the CNC high speed milling processor and the PC-acquisition system processor makes the system able to have information about the status of the machining process (i.e. on/off) at every moment.

Finally, the preliminary milling test on which this work finds its bases has been developed using Steel 114 as a working material. In future, checking other materials has to be taken into account and also the possibility to use different kind of sensors.

Conclusions

In this paper, a new concept of CNC machine tool as a multiprocessor system was proposed. The concept is closely related to the control method of a CNC multiprocessor machine. The proposed method involves a few steps focused on increasing productivity of the machining process and keeping the surface quality requirements of the finished piece. To verify the concept a complete experimental set up based on a machine tool multiprocessor system was performed.

Experimentally, it is possible to clarify the working region online and to support the relationship between quality and productivity, according to technical requirements.

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А. Рамирес

Процесс обработки деталей на станках ЧПУ с многопроцессорным управлением

Станки с ЧПУ обычно работают по заранее написанной жесткой программе. Однако в действительности это может приводить к возникновению вибраций в процессе обработки деталей. Возникновение этой вибрации может быть связано с конфигурацией обрабатываемой детали, траекторией и состоянием рабочего инструмента, материалом обрабатываемой детали. В настоящей работе предлагается метод управления станком с ЧПУ как многопроцессорной системой. Метод включает несколько шагов, ориентированных на увеличение производительности машины при сохранении заданного качества обработанной детали. Для подтверждения результативности предложенного метода были проведены эксперименты с высокоскоростным фрезерным станком с ЧПУ, снабженным акселерометрами и соединенным с дополнительным процессором стандартного PC. Экспериментально показано, что можно найти оптимальные рабочие параметры и перейти в режим адаптивного управления, исключающий возникновение вибраций рабочего инструмента, и, поддерживая в соответствии с техническим заданием качество обработки, получать максимальную производительность.

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