# A proposed adaptive current controller for CNC-milling systems

E. Soliman
*Department of production Engineering, University of Alexandria, Egypt 21544* [1]
F. Ismail
*Department of Mechanical Engineering, University of Waterloo, Canada N2L 3G1*

This paper presents a simple fuzzy logic adaptive controller for CNC-milling systems. The objective of the controller is to keep the cutting torque within prescribed limits. The controller employs the spindle drive current signal of an industrial type milling system for monitoring and controlling the performance of the system. The amplitude and root mean square of the current signal are used as bases for performance assessment of the system. The controller uses a set of control rules to regulate the feedrate on-line. The regulation of the feedrate is implemented by modifying the word address commands sent to the NC control unit of the milling system. The controller has a software module that controls the transfer of the word address control commands to the NC control unit. Cutting tests were conducted to examine the performance of the controller. The results of the cutting tests show the success of the controller in achieving its objective under different machining conditions.

تقدم هذه الورقة البحثية مقترح لنظام تحكم تياري ذاتي التعديل لأنظمة التفريز ذات التحكم الرقمي. الهدف من نظام التحكم هو تثبت عزم القطع والإدارة عند حد معين . يعتمد نظام التحكم على قياس شدة التيار لمحرك عمود الإدارة لنظام التفزير الرقمي و حيث يتم تحديد مقدار والجذر التربيعي المتوسط لإشارة شدة التيار. يستخدم نظام التحكم مجموعة من القواعد المنطقية للتحكم في معدل التغذية. ويتم تغير معدل التغذية بتغيير الأوامر التي يتم إرسالها لوحدة التحكم الخاصة بنظام التفريز الرقمي. تم اختبار نظام التحكم المقترح من خلال مجموعة من اختبارات القطع العملية. أثبتت نتائج الاختبارات نجاح نظام التحكم المقترح في الوصول إلى هدفه وتثبيت عزم القطع والإدارة عند ظروف تشغيل مختلفة.

**Keywords:** Adaptive control, Fuzzy logic, CNC machining, Machine tools

## 1. Introduction

Computer Numerical Control (CNC) Machine Tools CNC machine tools are the backbone of modern manufacturing industry. They can be used as stand alone machining systems or production units. They can also be integrated into flexible manufacturing systems via computer control. Employing CNC machine tools usually requires a large capital investment. Therefore, it is necessary to control their performance to ensure safe operation and thus to protect the investment.

Research work related to the performance of CNC machine tools focused on the design of servo controls. The objective of servo controls design is to ensure that main and feed drives follow precisely motion commands; position, spindle speed and feedrate commands. This would assure dimensional and geometrical accuracy of production. Several servo control designs have been developed and implemented successfully [1-3]. However, they require hardware modifications of the CNC system. These modifications are not usually acceptable by manufacturers due to the risks involved. However, it is essential to consider them for new CNC system designs.

Adaptive control of CNC machine tools also focuses on performance improvement of CNC machine tools. However, it is concerned with the machining process rather than the CNC machine tools servo controls. The objective of an adaptive controller for a CNC machine tool is to keep the cutting forces or cutting torque within the acceptable limits for the machining system. These limits are based on the mechanical and electrical capabilities of the system. Using the machining system beyond its capabilities results in excessive tool wear,

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[1] e_soliman@yahoo.com

tool breakage and unacceptable production quality. This results in long idle time for tool changing and setting and consequently lowered productivity and increased production cost. Also, the hardware of the machining system, mechanical elements and electrical and electronic components, can be endangered.

The operation of an adaptive controller depends on measuring the cutting force or cutting torque using a force or torque dynamometer. The measured signal is then digitally processed and its level is compared with a prescribed level that corresponds to the capability of the machining system. Based on this comparison, an adaptive controller would regulate the feedrate or the depth of cut to keep cutting forces and cutting torque within the prescribed limits. Regulating the depth of cut requires modification of the NC part program on line, which is not usually a straightforward task. Therefore, most research work is focused on regulating the feedrate [4-6].

Most adaptive controllers require a model of the machining system. The model can be static or dynamic, but dynamic models are more accurate in representing machining systems. Several authors developed models for machining systems and used them to build adaptive controllers that regulate the feedrate [7-8]. Controllers were tested successfully under different machining conditions. However, two types of difficulties are associated with adaptive controllers; first, the measured model parameters directly affect the success of adaptive controllers. Errors in these measured parameters can result in a failure of the adaptive controller. Also, variations in the dynamic characteristics of the machining system due to use or aging of the system can result in failure of the adaptive controller. Second, regulation of the feedrate usually involves modifications of the hardware of the machining system. These modifications are not usually acceptable by manufacturers due to the risks involved.

Y. S. Tarng and Y. S. Wang [9] developed a fuzzy logic adaptive controller for constant torque in turning. The model of the machining system was replaced by a set of fuzzy rules. The controller employed the cutting force signal to determine the turning torque. Then, it used the calculated torque to regulate the feedrate in order to keep the turning torque within specified limits. Simulations of the controller and the machining system showed the success of the controller in keeping a constant turning torque.

E. soliman and F. Ismail [10] developed a rule based adaptive force controller for milling systems. The controller monitored the machining system using the cutting force signal and used it to regulate the feedrate. The controller had the advantage that it was software based, that is no hardware modifications were required. However, the controller had two disadvantages; first, the controller required installing a force dynamometer. Dynamometers are expensive and delicate. Also, for some systems, space limitation becomes a problem. Second, the controller was two to one mapping from force levels (amplitude and RMS) to control action. This resulted in relative instability of the controller, which kept changing the feedrate without significant effect on system performance.

The purpose of this paper is to introduce a simple fuzzy logic adaptive current controller for CNC-milling systems. The proposed controller does not require a model for the system, rather, it is based on a set of fuzzy control rules that represent the system control methodology. The controller employs the spindle drive current signal for monitoring the machining process. The spindle drive current signal is available on most industrial machining systems. Therefore, there is no need to install a force or torque dynamometer. Moreover, the controller does not require any modification of the hardware of the machining system, which makes it a considerable candidate for industrial applications.

## 2. Design of controller

Several cutting tests were first conducted to examine the current signal under no load conditions. The purpose of these tests is to establish bases for the design of the controller. Tests were conducted at different spindle speeds. For each test, the spindle drive current signal was recorded (experimental set up is described in the following section). Results of the tests showed that the current signal has a sinusoidal form with an amplitude range from 6 to 8 amperes. The frequency of the signals is either 72.5 or 140 Hz, depending of the spindle speed. Fig. 1 shows samples of the current signal under no load condition. Fig.1-a is typical for spindle speeds less than 780 RPM while fig.1-b is typical for spindle speeds higher than 780 RPM. The shown signals correspond to one of the three phases of the spindle drive motor. It reflects the relative value of the cutting torque rather than the actual torque values.

The structure of the controller is shown in fig. 2. The fuzzification interface takes the current signal and calculates its amplitude (AMP) and root mean square (RMS) values over periods of time. Each period ranges from 0.2 to 5 seconds depending on the feedrate. Also, the distance moved during the sampling period ranges from .5 to 5 mm. A recursive subroutine is designed to ensure that the sampling period and distance are within limits when the feedrate is changed. The ranges for the sampling period and sampling distances are arbitrarily selected. They are chosen to be short enough to ensure alert controller, but not too short to avoid many interruptions of the cutting process. Then the AMP and RMS values are converted into levels, (AMPL) and (RMSL). The levels are calculated according to the following equations:

$$\mathrm{AMPL} = \frac{\mathrm{AMP} - 10.0}{1.67} + 1 ,$$

and,

$$\mathrm{RMSL} = \frac{\mathrm{RMS} - 7.1}{1.17} + 1 .$$

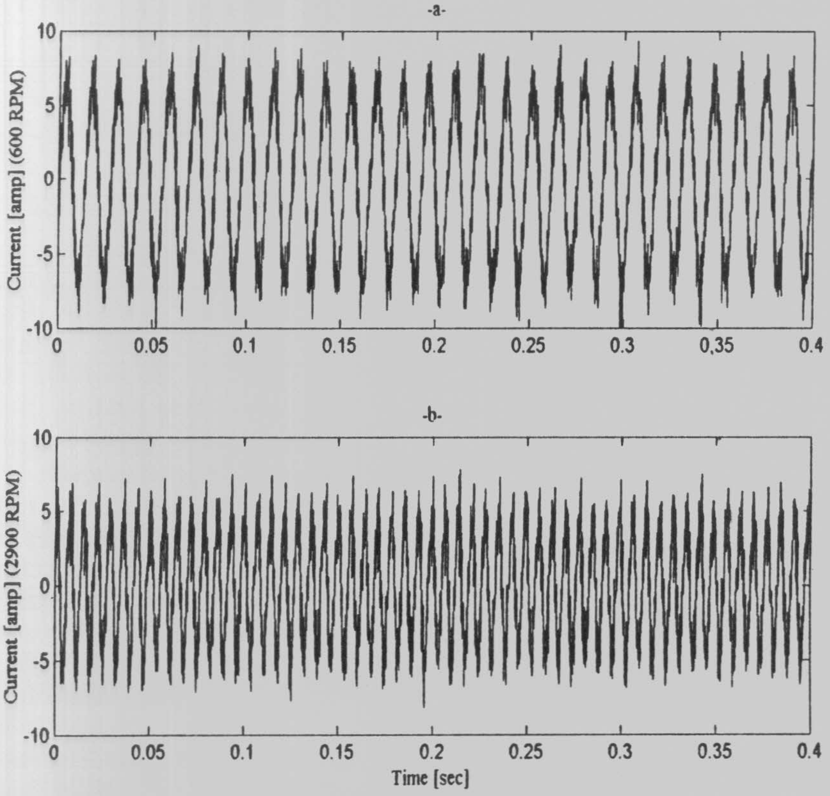

Fig. 1. Spindle drive current signal under no load conditions; a) at spindle speeds less than 780 RPM, b) at spindle speeds higher than 780 RPM.

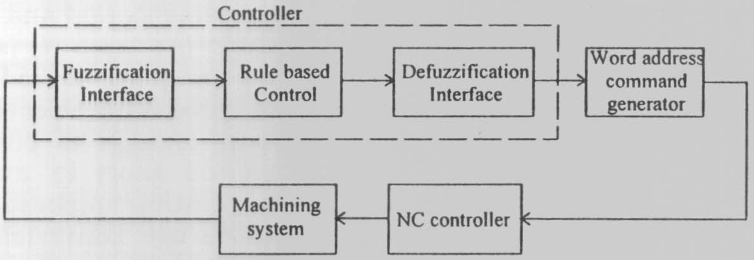

Fig. 2. Structure of the fuzzy adaptive controller.

A current signal with amplitude of 10.0 amperes is mapped to AMP level one,

$$\frac{10-10}{1.67}+1=1,$$

and RMS level one,

$$\frac{10/\sqrt{2}-10/\sqrt{2}}{1.67/\sqrt{2}}+1=1.$$

On the other, a current signal with amplitude of 25.0 amperes, or higher, is mapped to AMP level ten,

$$\frac{25-10}{1.67}+1=10,$$

and RMS level ten

$$\frac{25/\sqrt{2}-10/\sqrt{2}}{1.67/\sqrt{2}}+1=10.$$

The AMP of the current signal is an indication of peaks in the cutting torque during interrupted cutting. It is important for guarding the process from spikes in cutting torque, e.g. when the tool engages the workpiece or when there is a step in the workpiece. The RMS of the signal is an indication of cutting torque used for continuous cutting. It is important for guarding the cutting tool from stalling during cutting. These levels are arbitrarily selected for the machining system under consideration. They can be different for other machining systems and for other control strategies.

The rule base of the controller comprises 80 rules. These rules are listed in table 1.

Table 1
Control rules for the rule based controller

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RMSL | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 5 |
| | 2 | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 5 |
| | 3 | | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 5 | 6 |
| | 4 | | 2 | 2 | 2 | 2 | 3 | 3 | 5 | 6 | 7 |
| | **5** | | | 2 | 2 | **2** | 3 | 5 | 6 | 7 | 8 |
| | 6 | | | 3 | 3 | 3 | 5 | 5 | 7 | 8 | 8 |
| | 7 | | | | 3 | 5 | 6 | 7 | 8 | 8 | 9 |
| | 8 | | | | 5 | 6 | 7 | 8 | 8 | 9 | 9 |
| | 9 | | | | | 7 | 8 | 8 | 9 | 9 | 10 |
| | 10 | | | | | 8 | 8 | 9 | 9 | 10 | 10 |
| | | 1 | 2 | 3 | 4 | **5** | 6 | 7 | 8 | 9 | 10 |
| | | AMPL | | | | | | | | | |

Each rule takes the form of If. Then statement. For example, If the AMPL is 5 and the RMSL is 5, then the control action level is 2. The control rules are selected based on experience with the machining system under consideration and can be different for other systems. The crossed control action levels in table 1 imply inapplicable control rules. The determined control action level is translated into a feedrate change according to table 2. For example if the feedrate is 300 mm/min and the control action level is 2, then the feedrate will be changed to 330 mm/min. Then, if the control action is 9, the feedrate will be reduced to 165 mm/min. From Table1 it can be seen that the controller target is to keep the current signal AMPL and RMSL at the target levels 4 or 5. At lower level, the controller increases the feedrate. The increase in the feedrate is proportional to difference between the signal levels and the target levels. At signal levels higher than the target levels, the controller decreases the feedrate. At level one, the controller assumes no cutting is taking place and feedrate is not changed. This method of regulating the feedrate is different from the method given in reference [10], where a feedrate level was assigned to each AMPL and RMSL. Experimental work will show that the present technique will result in improved system stability.

Table 2
Defuzzification of control actions

| Control action level | Feedrate change % |
|---|---|
| 1 | 0 |
| 2 | ↑ 10 |
| 3 | ↑5 |
| 4 | 0 |
| 5 | 0 |
| 6 | ↓ 25 |
| 7 | ↓ 30 |
| 8 | ↓ 40 |
| 9 | ↓ 50 |
| 10 | ↓ 60 |

The commanded change in the feedrate is translated into word address format. Then commands are sent to the serial port of the numerical control unit via the control word address generator section of the controller. A detailed description of this section is given in reference [10] and will not be discussed in the present work.

## 3. Experimental work

### *3.1 Experimental set-up*

Cutting tests were conducted on a 3-axis OKK vertical milling machine. The machine spindle has a two-stage gearbox, with speed ranges from 150 to 780 RPM and from 780 to 3000 RPM. The spindle drive can provide up to 20 KW. The machine has a magazine that can hold up to 25 cutting tools. The machine is equipped with a FANUC 11 numerical control unit. Programs can be input to the control unit from the keyboard or from a PC via a serial communication port. Fig. 3 presents a schematic diagram of the machining system. The motion control unit provides power and motion commands to the machine spindle, feed drives and the magazine. It, also, provides several signals for monitoring machining operations. The spindle drive current signal is selected for the current work as it is available on most CNC-milling systems. The cutting tool is a SNDVIK end mill with three carbide inserts.

A National Instruments data acquisition card DAC (MIO-16E) is used to collect the spindle drive current data. The DAC is installed in a PC that is connected to the numerical control unit via the serial port. The sampling rate of the current signal is 5000 Hz. The serial connection is used to send G-code commands to the machining system. A module devalued using the C++ programming language is used to handle the transfer of G-code from the PC to the numerical control unit.

### *3.2. Experimental results and discussions*

Three cutting tests were conducted to examine the performance of the controller. The cutting parameters used for these tests are listed in table 3.

These parameters are selected to cover a wide range of machining conditions that can be realized by the CNC-milling system.

Fig. 4 shows the results of test 1. Fig. 4-a shows the spindle drive current signal in amperes. Fig. 4-b shows the levels of the AMP and RMS of the current signal, AMPL and RMSL. Fig. 4-c shows the levels of the control action as generated by the controller. Fig. 4-d shows the commanded feedrate in mm/min. From the figs, it can be seen that at the beginning of the cut, and before the tool fully engages the work part, the controller increased the feedrate above the setting value,

Table 3
Parameters for cutting tests

| Test No. | Depth of cut (mm) | Starting feedrate (mm/min) | Spindle speed (RPM) | Immersion |
|---|---|---|---|---|
| 1 | 4 | 360 | 800 | Full |
| 2 | 3 | 450 | 1500 | Full |
| 3 | 6 | 300 | 1000 | Half-down |

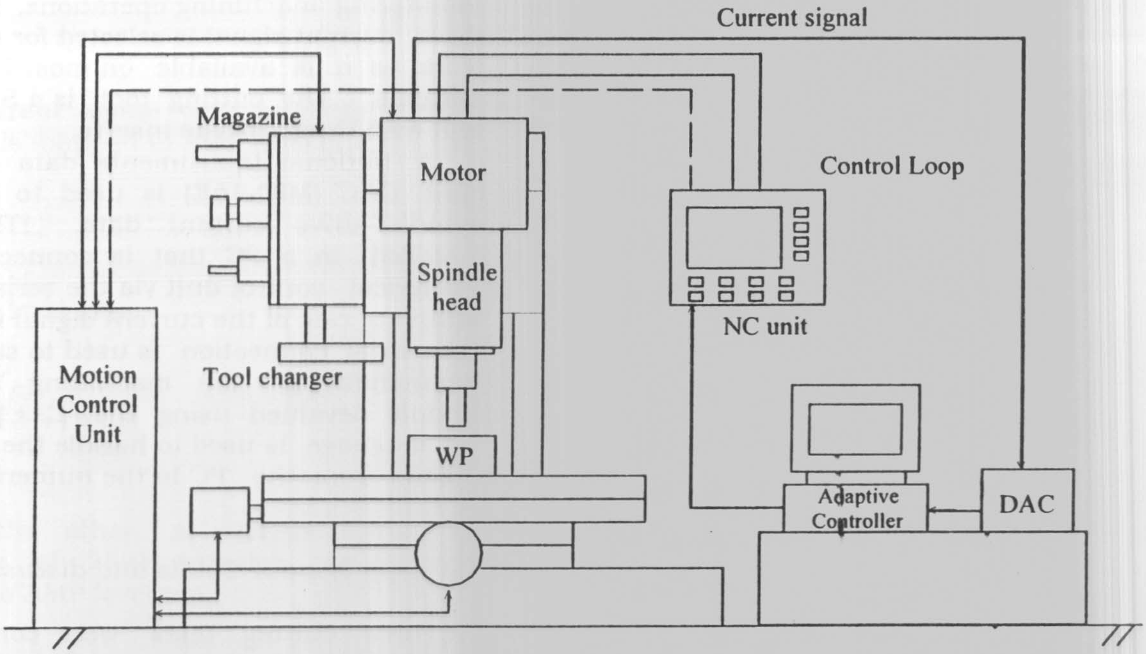

Fig.3. Experimental set-up.

360 mm/min. This is because the levels of the amplitude and RMS of the current signal were below the target levels. However, when the tool fully engaged the work part, the current signal levels exceeded the allowable limits, as specified by the control rules of table 1, and as a result, the controller commanded a decrease in the feedrate, from 378 mm/min to 75 mm/min, as shown in fig. 4-d. After that, the controller slightly adjusted the feedrate to 78 mm/min and cutting continued at this level of the feedrate.

The results of test 2 are shown in figs. 5-a, 5-b, and 5-c. In this test, the engagement between the tool and the work part was not gradual as in test one. The tool instantly and fully engaged the work part. As a result, there was a sudden increase in the levels of the current signals as shown in figs. 5-a and 5-b. The controller responded quickly to this sudden increase in the levels of the current signal, and decremented the feedrate from 450 to 119 mm/min. Then, the controller started to cautiously increase the feedrate in order to achieve the maximum possible feedrate. It, slowly, increased the feedrate to 167 mm/min. After that the cutting test was terminated.

The results of test 3 are illustrated in figs 6-a, 6-b, and 6-c. From fig. 6-a it can be seen that there is a large peak in the current signal at the beginning of the cut, during the first two seconds. There was no cutting during this period, and the peak is due to the setting of the spindle speed from 800 to 1000 RPM. The peak is reflected as an abrupt increase in the AMP and RMS levels of the current signal, as shown in fig. 6-b. As a result, the controller commanded a decrease in the feedrate, from 300 t0 180 mm/min. After speed setting, the tool engaged the work part and the controller decremented the feedrate to 75 mm/min. Starting from this point, the level of the RMS of the current signal was almost constant. However, there were unexpected variations in the level of its amplitude, and the controller kept adjusting the feedrate within the range from 75 to 106 mm/min. After that the tool started moving out of the cut and the controller started to increase the feedrate as shown during the period from 70 to 80 seconds in figs 6-b and 6-c. These unexpected variations could not be reasoned till the tool completely cleared the work part and a broken tooth could be observed. The controller could not detect the tooth breakage, however, it could manage to keep the current signal levels within the desired limits. A tool breakage detection module can be added to the controller to improve its industrial applicability. However, tool breakage detection is outside the scope of this paper.

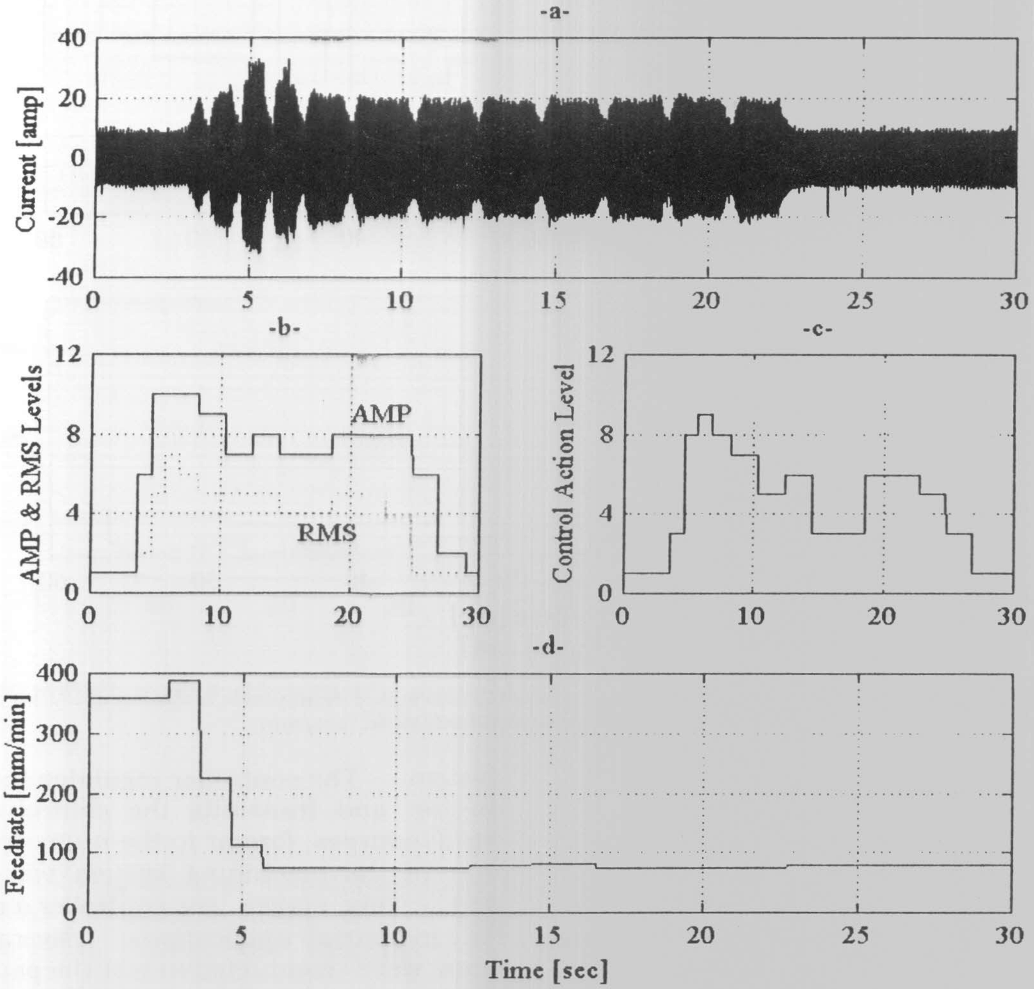

Fig.4. Results of cutting test 1; a) Spindle drive current signal in amperes, b) AMP and RMS levels of the current signal, c) Control action level, d) Commanded feedrate in mm/min.

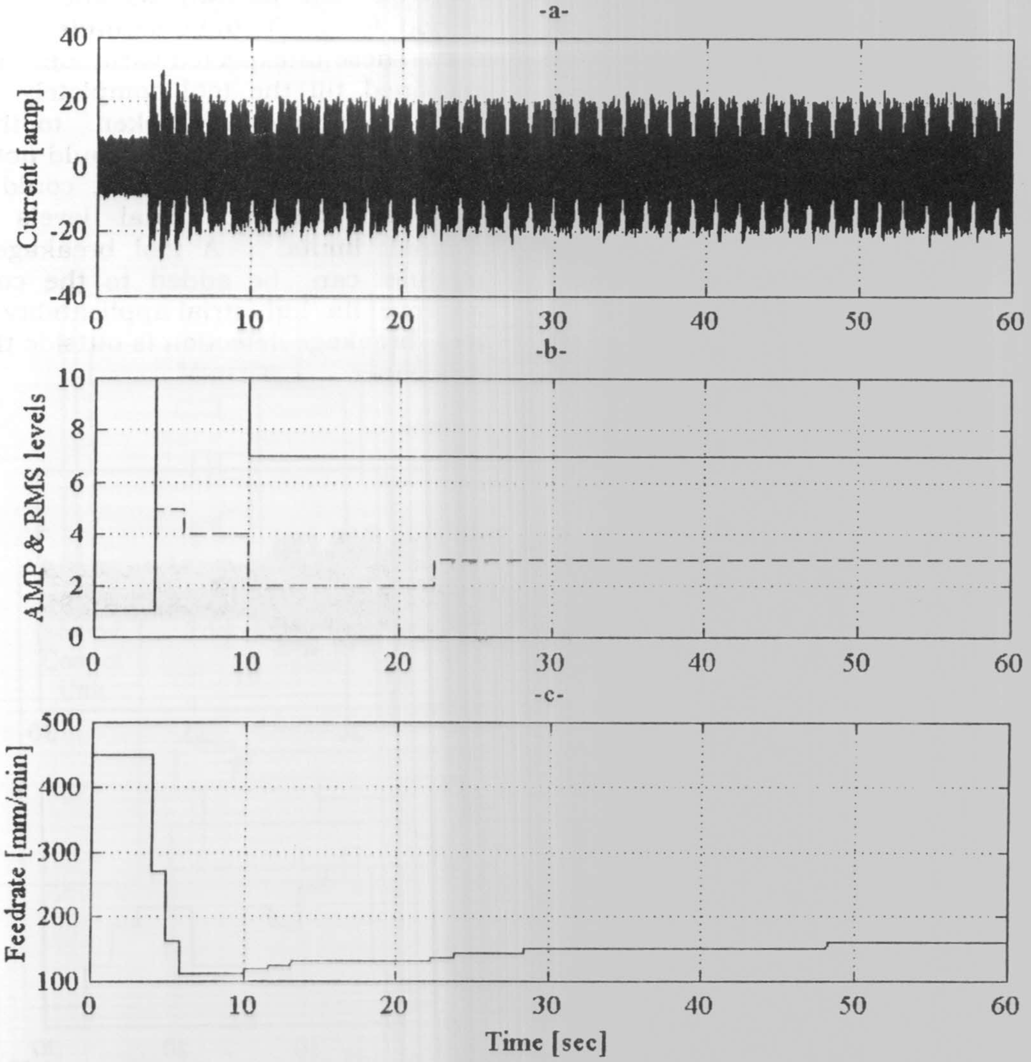

Fig.5. Experimental results of cutting test 2; a) Spindle drive current signal in amperes, b) AMP and RMS levels of the current signal, c) Commanded feedrate in mm/min.

## 4. Conclusions

A simple fuzzy adaptive controller for monitoring and improving the performance of CNC-milling systems has been developed and implemented. The controller employs the main spindle drive current signal of an industrial type milling system as a representative of the condition of the machining operation. The objective of the controller is to keep the current level within prescribed limits that depend on the capability of the machining system. The controller regulates the feedrate on-line and transmits the control action in word address format to the numerical control unit of the machining system via the serial port. This makes the controller a candidate for industrial applications. Several cutting tests were conducted to test the performance of the controller. Experimental results proved the success of the controller in protecting and improving the performance of CNC-milling system by on-line manipulation of the feedrate.

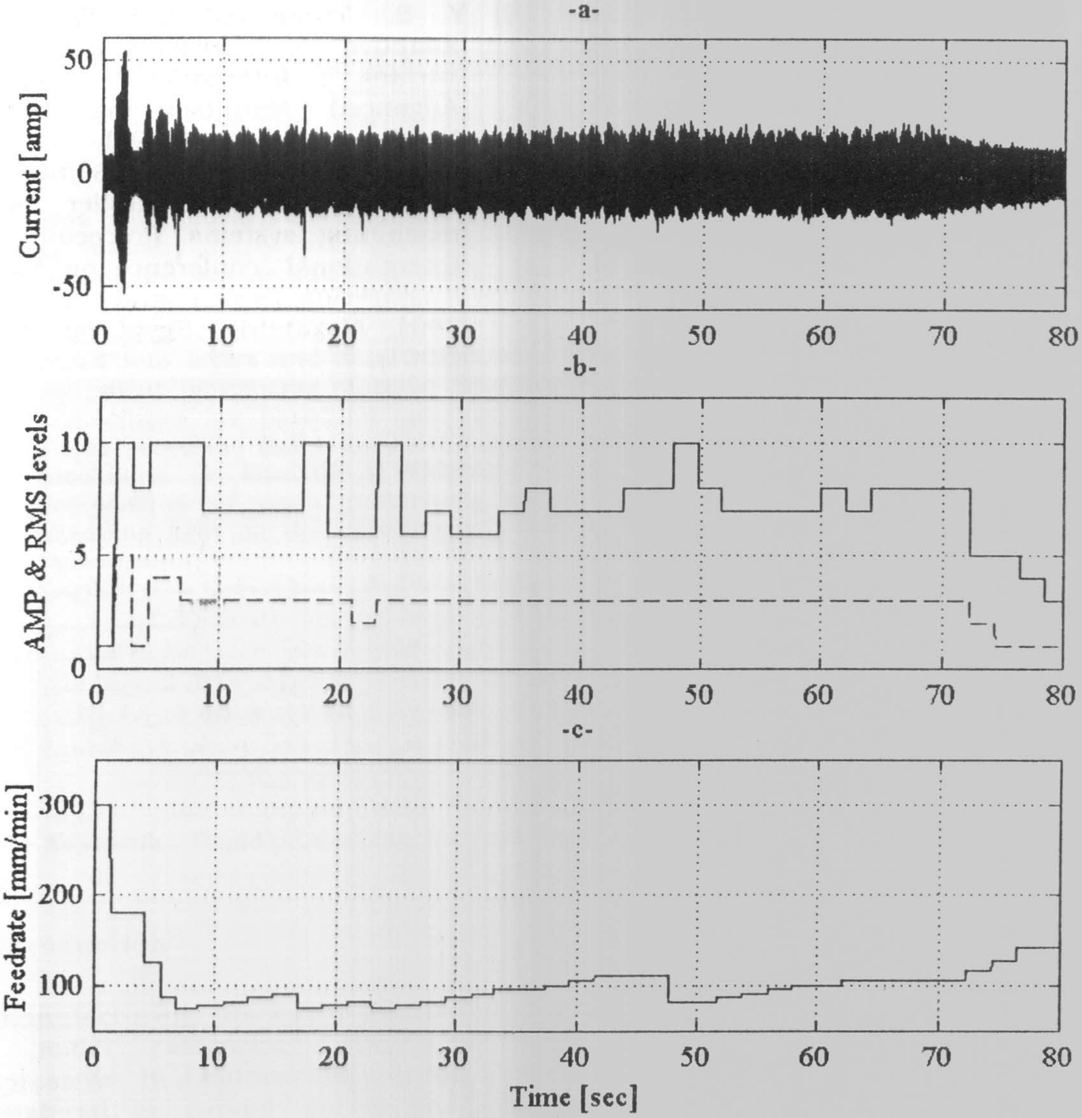

Fig.6. Results of cutting test 3; a) Spindle drive current signal in amperes, b) AMP and RMS levels of the current signal, c) Commanded feedrate in mm/min.

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