ADVANCES IN MANUFACTURING SCIENCE AND TECHNOLOGY Vol. 37, No. 1, 2013
DOI: 10.2478/amst-2013-0007

A FUZZY CONTROL STRATEGY IN THE TURNING PROCESS

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Summary

This paper presents a fuzzy approach to automatic feed rate correction during rough turning with inconstancy of both depth of cut and machinability of material. Additional sensors are not required in this approach. It makes use of modern numerical controllers. In every interpolator (IPO) cycle, a new adaptive value of feed rate is activated by means of synchronous actions based on current power consumption. Aggregate fuzzy functions have been used to calculate new values of feed rate and the effect of intelligent reaction to the alterations of external factors has been achieved. This approach also enables the calibration of the main drive dynamics adjusting it to the actual goals of the machine cutting operations.

Keywords: adaptive feed rate control, fuzzy control, synchronous actions, rough machining

Rozmyta strategia sterowania w procesie toczenia

Streszczenie

W pracy przedstawiono podejście rozmyte do automatycznej korekcji posuwu w zgrubnej obróbce tokarskiej o zmiennym naddatku i różnej skrawalności materiału obrabianego. Podejście nie wymaga instalowania dodatkowych sensorów w przestrzeni roboczej obrabiarki. Wykorzystano możliwości nowoczesnych układów sterowania numerycznego. Rzeczywiste zapotrzebowanie mocy przez napęd główny obrabiarki określono przez użycie akcji synchronicznych wbudowanych w program sterujący. Było podstawą do ustalenia się w każdym cyklu (IPO) nowej wartości programowego współczynnika korekcji. Do ustalania nowych wartości posuwu użyto rozmytych funkcji agregacji. Uzyskano efekt inteligentnej reakcji na zmiany czynników zewnętrznych. Zastosowane podejście umożliwia także prawidłowe ustawienie dynamiki napędu głównego obrabiarki. Uwzględnia rzeczywiste potrzeby w realizowanych operacjach obróbki skrawaniem.

Słowa kluczowe: adaptacyjne sterowanie posuwem, sterowanie rozmyte, akcje synchroniczne, obróbka zgrubna

1. Introduction

Engineers have always searched for the increase of efficiency and infallibility of the turning process as these two factors are crucial to the final

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result of the process as far as the workload and costs are concerned. This research goes in many different directions; many of which have given the results already hard to improve. At present, the biggest potential in rough machining can be seen in the increased use of adaptive control (AC) which adjusts the cutting parameters to the actual conditions in the cutting zone. The matter is to take the actual cutting tool load resulting from cutting allowance, local machinability and the condition of the tool into consideration. AC for the rough machining must also take the limitations resulting from the main drive of the machine tool and the cutting insert durability into account in order not to cause the machine damage and therefore the unnecessary stoppage in work. Additional advantages of AC are as follows: increased efficiency due to shorter machining time and breaks, longer life of the blade insert with its maximum use, smaller number of rejects and worker's interventions, increased degree of the automation of the process and easier generation of control program for the machine tool.

Generally, rough turning can be perceived as a non-linear system with very uncertain dynamics. At present, the cutting parameters for CNC turning machines such as: feed rate, cutting depth and speed are programmed off-line, and corrected manually by a machine operator. In case of rough machining the off-line optimization is very difficult or even impossible, when the cutting allowance indicates significant inconstancy in volume and machinability. It usually results in lower cutting parameters. It is possible to correct feed rate and speed manually. However, it requires certain skill and experience from the worker as well as his constant assistance during the cutting operation.

Automation of rough machining requires AC in the given workplace. This method guarantees optimal and safe machining. Traditional approach to AC is associated with Machine-Fixture-Workpiece-Tool system (MFWT). Traditional approach to adaptive control is associated with building force sensors, deflection sensors, pressure sensors, temperature sensors, heat emission sensors, vibration sensors, acoustic emission sensors, etc. into MFWT system. Those solutions are often costly as they entail the development of MFWT, the need for highly qualified workers, regulation system calibration and they may also require external PC along with the proper, efficient communication protocols for the regulation strategy. In many cases the development of MFWT is technically impossible or too expensive. Therefore the application of AC in CNC machine tools, popularized since the 1960's, isn't widespread. The most published and scrutinized approaches are still limited to laboratory research and the examples of the common use of new methodology remain unknown.

New, fully-digital CNC, with quick processors and efficient data bus system should be the breakthrough as far as AC popularization is concerned. Due to them no additional equipment is necessary since they use (thanks to system variables) direct information about the load of the motive unit in the machine tool. Built-in servo-trace of various drive work parameters make it easier for the operator to learn them and to learn the flow inconstancy. At the same time, the operator (programmer) with the access to system variables can modify the parameters of the operation by means of synchronous actions, and what is more deal with the situations requiring immediate interventions (such as worn out blades). Those new, more and more conventional abilities of machines have to be supported by intelligent machining parameters modification strategies and the strategies for the emergency stoppage of the machining process. The results of the research focused on such strategies and conducted by the Department of Manufacturing Technology and Automation, Siemens (as a producer of a CNC control system called SINUMERIK) along with the plants that want to apply those strategies in practice are presented in this article.

Basically, the knowledge of the abilities, limitations, preferences and perspectives of the AC development hasn't changed since the beginning of XXI century. The book of Ioannou and Suna [1] was unquestionably the crucial work summarizing achievements in the field of machine cutting adaptive control in the period between 1970 and the mid 1990's. In the article [2], its author made a recap of the tool monitoring and machining process at the end of XX century. The author notices that in spite of numerous monitoring methods tested in laboratories only a few of them found practical use. In conclusion, the author names the advantages of using multi-sensor systems. The analysis of publications shows the tendencies in this field. Form the number of articles [3-7] we can draw the conclusion that artificial intelligence, especially fuzzy logic is becoming more and more important in AC systems. Liam et al. [7, 8] presents Self-organizing fuzzy control (SOFC) where, during the turning process, the learning strategy is being continually updated in the form of fuzzy rules.

The dominant method for modelling the correlation between input variables and output variables in the cutting operation is artificial neuron network (ANN) [5, 9]. Based on the integration of two subsystems: the neural network-based, in-process surface roughness prediction (INNSRP) subsystem and the neural network-based, in-process adaptive parameter control (INNAPC) subsystem, which use not only the cutting parameters data, but vibration signals from accelerometer sensor as well, the neural-networks-based surface roughness adaptive control (INNSRAC) system has been proposed [9].

However, it appears that we face stagnation as far as new ideas for rough turning. The specific character of this process makes the majority of researchers and engineers apply Adaptive control constraint (ACC) for this phase of the operation. They aim at the constant cutting tool wear. This approach does not guarantee the proper chip shape in case of hard workpiece even though it is necessary for the full automation of the operation. At present, the most promising applications concern the programmed feed rate correction based on system variables coming directly from the control system which represent the load of the main spindle [10-12]. Such solutions, if they are built in the control system, eliminate the need for manual parameter optimization of the program in rough machining. In effect, the machining cycle is 40% shorter. The approach is based on reducing “the air cutting” by means of tool-part touch control – as presented in the work [13]. Unconventional approach was presented by Cus et al. [14] in form of adaptive neuro-fuzzy inference system (ANFIS) based on ant colony optimization method. The method has to initiated on external computer, though. Among recently published works, Ratava et al. [15] is also worth noticing as it tests an adaptive fuzzy control system which allows to lower feed rate when cutting instability (chatter) is detected or in case of excessive load of the drive. Nevertheless, machine-fixture-workpiece-tool system had to be connected with vertical and horizontal acceleration sensors as well as acoustic emission sensor. Thus the (in)stability of the cutting operation could be determined.

2. Methodology

We propose an approach which is a continuation of the method presented in [11], where the effective method for the regulation of a wheelset with various, unpredictable cutting allowance and changeability of the workpiece which is difficult to machine was displayed. In this case, the high rigidity of the underfloor wheel lathe plus a great power of the main fluid drive successfully eliminated undesirable chatter and over-regulation of the control system. That strategy was tested in normal production conditions with relatively low parameters.

The method assumes the cutting operation control by means of the programmed correction coefficient which is expressed by system variable *$AC_OVR* based on the monitored main drive load signal which is available as a system variable *$AA_LOAD*[*spindle*]. Two steps of calculation have been taken in every IPO cycle:

Step 1: Establishing the correction coefficient (W_k) based on the formula:

$$W_k = \exp((-5/M_z^2)(M_a^2)) \quad \text{for } M_a < M_z \tag{1}$$

$$W_k = \exp(-10/(1-M_z/100)(M_a/100-M_z/100)^2) \quad \text{for } M_a > M_z \tag{2}$$

where: M_a – the current percentage of torque use, M_z – the percentage of nominal torque use set by an operator.

Step 2: Establishing a new programmed correction coefficient (O_n) by using fuzzy aggregate functions of correction indicator and current value of programmed correction coefficient (O_a):

$$O_n = 200\cdot(O_a/200+W_k-W_k\cdot O_a/200 \quad \text{for} \quad M_a < M_z \tag{3}$$

$$O_n = W_k \cdot O_a \quad \text{for} \quad M_a > M_z \tag{4}$$

The relationship between W_k and M_a was designed (formulas (1), (2) and Fig. 1), so as to make variables M_a, and W_k decrease at both ends of the range. When the needed situation is acquired, meaning M_a is similar to M_z, variable W_k should not be large. We should bear in mind that this relationship must adapt to the current parameter M_z. Aggregate functions (formulas (3) and (4)) which help to determine a new correction coefficient are presented in the Figures 2a and 2b. As a result, exemplary flows O_n as a function O_a and M_a, for established M_z, are displayed in the Fig. 3. It is an infinite set of continuous functions with the domain in the interval $M_a = (0,100\%)$ and the value set $O_n = (0,200\%]$.

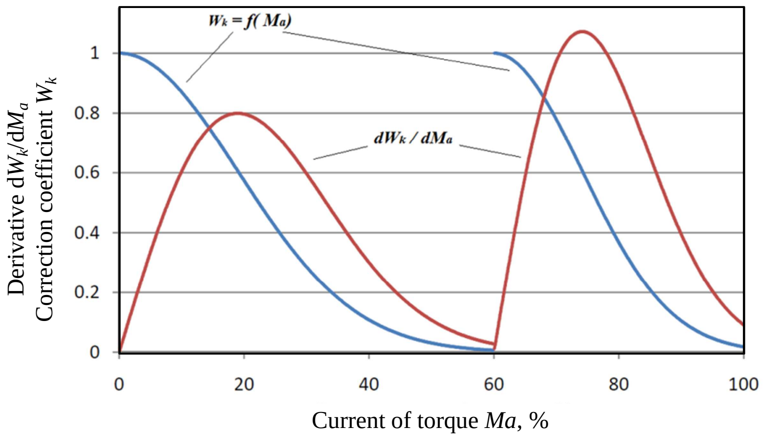

Fig. 1. Relationship between W_k and the current torque used and it's derivative for $M_z = 60\%$

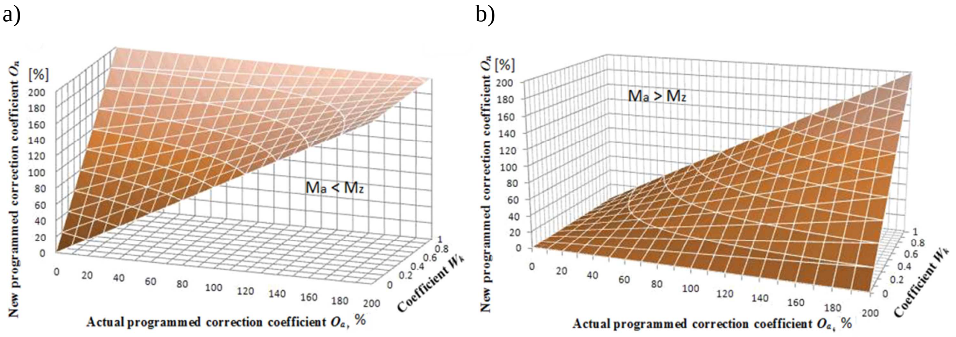

Fig. 2. Fuzzy: a) disjunction, b) conjunction O_a and W_k

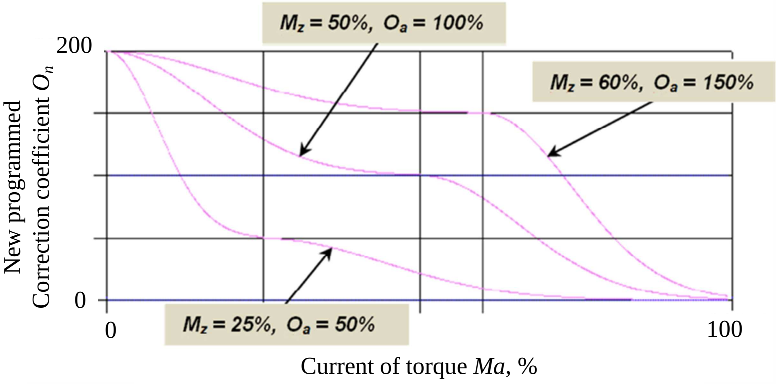

Fig. 3. Exemplary flows displaying programmed feed rate override O_n

The strategy is applied by means of activating synchronous actions which use arrays with variables of real type *$AC_PARAM*[*i*] and integer *$AC_MARKER*[*i*] designed specially for those actions. What is more, those actions employ the timer *$AC_TIMER*[*n*] and *$AA_IW*[*Z*], i.e.: a variable maintaining the current position of the blade in relation to the front side of the workpiece (workpiece coordinate system WKS). Those variables are used in order to program functions in accordance to the formulas (1)-(4), to record the data in every IPO cycle as well as to generate a report automatically after the trial is finished. If the report is generated during the trial, we run the risk of the processor failure. The reports were used to make the charts of the trials. Programmed feed override *$AC_OVR* has to be calculated in every IPO cycle, otherwise it's value would be set at 100%. For this reason, it's current value must be recorded each time, because it is taken into account while calculating O_n.

3. Test results

The tests were conducted at the laboratory station with CNC Lathe TUG56MN and SINUMERIK 810D. This equipment is not very stiff/rigid and has relatively low power (9kW) of the main drive. The tool bit with trigonal insert WNMG 08 04 08-TF was used for the tests. Steel E295 was chosen for machining. Programmed feed rate was 0.4 mm per revolution, cutting depth 1-3 mm. To achieve repeatable conditions the initial turning of the front and the cylinder was done in the same fixing as the test turning (Fig. 4).

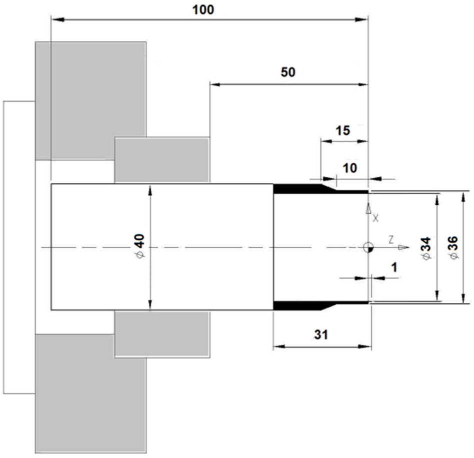

Fig. 4. Sample for the tests

Test results were shown in Fig. 5-7. Additionally, the chart of the cutting allowance was prepared on the basis of tool blade position on an axle *Z* and the knowledge of the part geometry. Moreover the photography of the attained surface was added. In test #1 (Fig. 5) the partial effectiveness of the method was observed. When the cutting allowance was 1mm the drive load was about 25%, but when it reached 60% the synchronous action was initiated and it set the multiplicative correction coefficient for the feed rate *$AC_OVR* at approximately

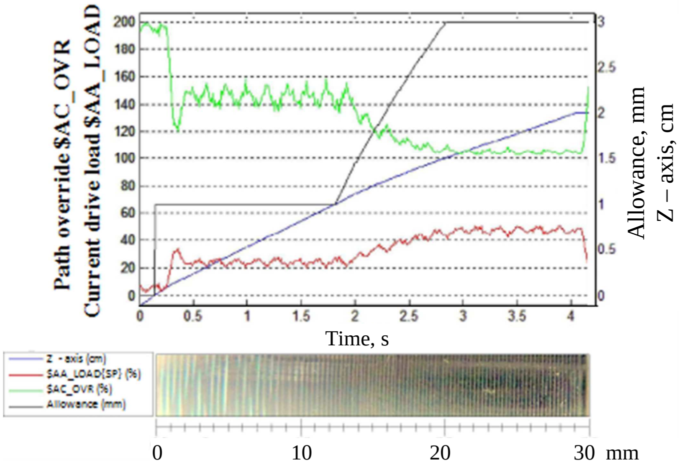

Fig. 5. The results of the trial before the modification of the formulas to *$AC_OVR*

145%. As a result, the cutting operation was accelerated, thus, theoretically, the process was 20% shorter. In case of 1mm cutting allowance and +/–2% for cutting depth that equals 3mm, the current value *$AC_OVR* is influenced by the disturbance causing oscillation of +/–10%. It was assumed that they are caused by the character of the function which calculates the current value *$AC_OVR*.

After conducting further experiments other, more flexible formulas (1), (2) and (4) were created.

$$W_k = k\cdot\exp((-5/M_z^2)(M_a^2)) \quad \text{for} \quad M_a < M_z \tag{5}$$

$$W_k = p\cdot\exp(-10/(1 - M_z/100)(M_a/100 - M_z/100)^2)+(1 - p) \quad \text{for} \quad M_a > M_z \tag{6}$$

$$O_n = W_k\cdot(O_a - d) + d \quad \text{for} \quad M_a > M_z \tag{7}$$

The introduction of coefficients $k = 0.1$, $p = 0.1$, $d = 25$ (Fig. 6) resulted in more smooth correction (Fig. 7). Overregulation was eliminated and the proper chip swelling/bulging was achieved. The surface obtained was without scratches and indicates the flawless control operation. There weren't favourable conditions for accretion when oscillation was eliminated.

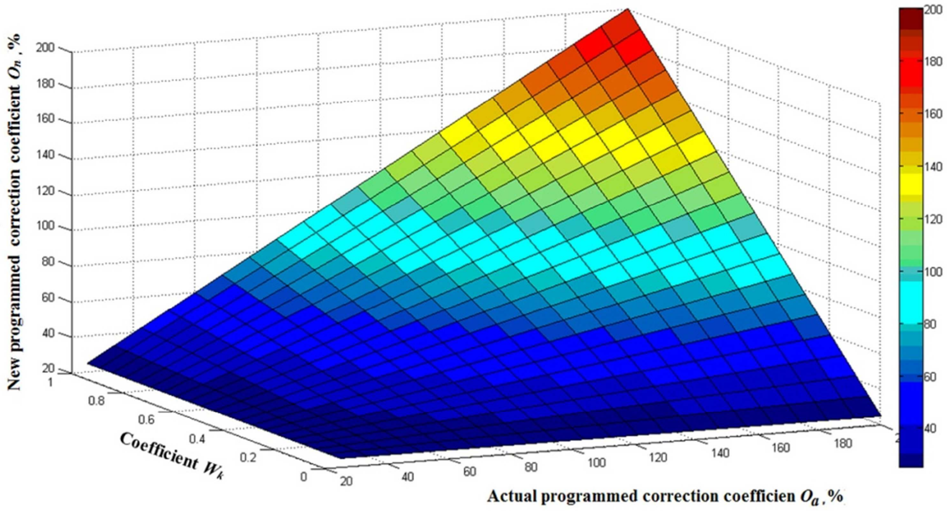

Fig. 6. The influence of *d* parameter on the fuzzy conjunction O_a and W_k (for $d = 25$)

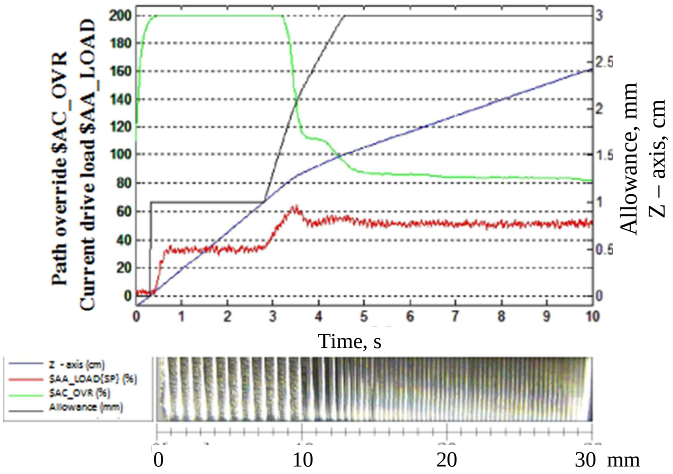

Fig. 7. The results of the trial after the modification
of the formulas to *$AC_OVR*

4. Summary

The presented control strategy is aimed at achieving the percentage indicator for the nominal torque of the main spindle drive which is set individually by an operator and moreover it takes nominal feed rate programmed for the particular surfaces into account. In practice, those two goals are very often contradictory. Presented approach enables a certain level of compromise in a given phase of a machining operation. It resembles the reaction of an experienced operator so it possesses the traits of an intelligent approach. Conducted research results confirm the effectiveness of logistic functions in creating an intelligent feed rate regulation set for turning process. Undoubtedly, the advantage of presented approach is the usage of existing capabilities of the control system, i.e.: minimizing capital costs for the purchase of force sensors, accelerometer sensors, temperature sensors, etc. The formulas for calculating a programmed feed rate correction coefficient is very flexible since it enables the operator to adjust the parameters k, p, d i M_z to the optimum value for the given operation and even parametrization if the machining operation is very complex.

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Received in October 2012