THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAȚI
FASCICLE V, TECHOLOLOGIES IN MECANICAL ENGINEERING, ISSN 1221-4566
2007

Adaptive-Optimal Control of Reconfigurable Machine Tool

PhD. eng. Ana Maria ALAMANO, PhD. eng. Niculai HAUK,
PhD. eng. EPUREANU Al.
Dunărea de Jos University GALATI

Abstract

This paper is presenting an optimal adaptive control of the cutting proces based on on-line re-identification. This approach is taking into account the margin optimizing criteria. We are considering the market success of the processed product. Starting with this idea, a software was designed to test the optimal adaptive cutting process. Also several simulations were performed to test algorithm reliability.
***Keywords**: System identification, Adaptive schemes, Optimal control.*

1. Introduction

Studying the nowadays solutions, tested or proposed only, concerning optimal and adaptive process control, it can be stated several issues:

a) cutting process optimization it is performed by computing the optimum values for the parameters in the design phase of the manufacturing process; consequently, these values are initialized to a constant value during processing;

b) parameters values adjusting it is performed at long periods, and it is not have the full effect of maximizing the performance variables of the processing;

c) concerning on-line monitoring, the information gathered it is used with considerable delay for the cyclic cutting parameters changing;

d) mathematical models which are used for the parameters values calculus are not resulted from the current process identification;

e) the process optimization algorithm it does not taking into account the market response regarding the product, and as well does not consider the real characteristics of every blank processed;

g) the online process monitoring techniques are improving continuously;

i) in the previous approaches of cutting process identification only the off-line techniques are considered.

2. Problem statement

It can be stated that in the nowadays control of cutting process, the real values of the parameters are not close to the optimum ones, we are showing that there are sufficient space range for increasing the performance parameters using an improved control without any additional expenses.

On-line optimization of cutting processes was limited because of the technical and economical environment. At the time, the challenging competition, as well as the technical improvement, imposes a new approach in order to increase competitivity of the products manufactured.

At the present time there are available systems able to continuously monitor several different parameters, including tool wear. These informations, digitally computed, with a high sample rate, can be easily processed, interpreted and stored. Combining these informations with the economical parameters is providing the advantage of deciding the cutting optimization parameters during the manufacturing. The total cost of processing, C_T is.

$$C_T = (\tau_b + \tau_a + \frac{\tau_{sr}}{n_b})c_\tau + \frac{C_{as} + Ces}{(N+1)T}\tau_b + C_i \qquad (2.1)$$

where:

- τ_b – it is the basic time, spent for the surface cutting;
- τ_a – auxiliary time;
- τ_{sr} –time needed for the tool change and adjustment of the tool, a component of the auxiliary time;

- $\mathbf{n_b}$ – the amount of blank processed between two successive reshaping;
- $\mathbf{c_\tau}$ – the sum of all expenses directly proportional with the time;
- $\mathbf{C_{as}}$ – tool cost;
- $\mathbf{C_{es}}$ – tool operating cost;
- $\mathbf{N}$ - number of reshaping cycles;
- $\mathbf{T}$ - tool durability;
- $\mathbf{C_i}$ - indirectly cost.

It is given the base time τ_b, calculate with the Taylor formula:

$$\tau_b = \frac{VT^m}{Cs^{1-x}t^{1-y}}.$$

Tool cost between two successive reshaping is:

$$C_s = \frac{C_{as} + C_{es}}{N+1}, \tag{2.2}$$

Considering the ratio between total cost and the chip volume we obtain $C_V = \frac{C_T}{V}$.

Considering $\frac{\tau_b}{T} = \frac{V \cdot T^{m-1}}{C \cdot s^{1-x} \cdot t^{1-y}}$ and note that $C_t = C_s + \tau_{sr} \cdot C_\tau$ it is obtained

$$C_V = \frac{1}{V}\left[\frac{V}{C \cdot s^{1-x} \cdot t^{1-y}}\left(T^m \cdot C_\tau + T^{m-1} \cdot C_t\right) + \tau_a C_\tau + C_i\right], \tag{2.3}$$

It is retained from this expression the volumetric cost depending of time as :

$$C_{Vt} = \frac{T^m \cdot C_\tau + T^{m-1} \cdot C_t}{C \cdot s^{1-x} \cdot t^{1-y}}, \tag{2.4}$$

For finding the maximum of this function with respect to durability T it is calculated:

$$\frac{\partial C_{V_t}}{\partial T} = \frac{mT^{m-1}C_\tau + (m-1)T^{m-2} \cdot C_t}{C s^{1-x} \cdot t^{1-y}}, \tag{2.5}$$

Analyzing the cost derivative depending to the durability $\mathbf{T}$ it is calculated the minimum function, corresponding to the economical durability

$$T_{ec} = \frac{1-m}{m}\frac{C_t}{C_\tau}, \tag{2.6}$$

Calculating cutting productivity

$$Q = \frac{V}{\tau_b + \tau_a + \frac{\tau sr}{n_b}}, \tag{2.7}$$

As: $\tau_b = \frac{V}{v \cdot s \cdot t} = \frac{V \cdot T^m}{c \cdot s^{1-x} \cdot t^{1-y}}$, $\quad \frac{1}{n_b} = \frac{\tau_b}{T} = \frac{V \cdot T^{m-1}}{C \cdot s^{1-x} \cdot t^{1-y}}$

it is obtained:

$$Q = \frac{1}{\frac{\tau_a}{V} + \frac{T^m + \tau sr \cdot T^{m-1}}{C \cdot s^{1-x} \cdot t^{1-y}}} \tag{2.8}$$

Computing $\frac{\partial Q}{\partial T} = 0$ relation it is obtained the maximum function corresponding to production durability represented as :

$$T_{pr} = \frac{1-m}{m} \cdot \tau_{sr}, \tag{2.9}$$

In figure1 it is presented the productivity and the cost dependence of durability.

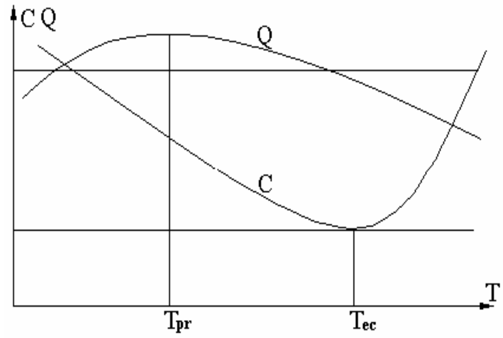


Fig. 1. *Productivity Q and cost c charts function of tool durability T*

As important parameter in the technical and economical defining it is considered the specific price $\mathbf{p}$ as :

$$p = \frac{\text{Selling price}}{\text{Surface area}} \tag{2.10}$$

The specific margin (ROL/min) it is defined with the expression :

$$B = (p - c)Q \tag{2.11}$$

It is obtained the margin formula:

$$B = \frac{C \cdot p \cdot s^{1-x} \cdot T^{1-m} - c_\tau \cdot T - c_s}{T + \tau_s} \tag{2.12}$$

By nulling the derivative it is calculated the

$$\frac{\partial B}{\partial T} = \frac{\left[(1-m)C \cdot p \cdot s^{1-x}T^{m} - c_\tau\right] \cdot (T + \tau_s) - C \cdot p \cdot s^{1-x}T^{1-m} + c_\tau \cdot T + c_s}{(T+\tau_s)^2} \tag{2.13}$$

equation (2.13) containing as unknown variable the durability, named optimum, **Top**.

The calculation of this equation allows the determination of - 31 -optimum durability. The optimum durability **Top** is given by expression:

$$T_{op}^m - \frac{(1-m) \cdot C \cdot p \cdot s^{1-x}}{c_\tau} \cdot \frac{T_{op} - T_{pr}}{T_{ec} - T_{pr}} = 0 \tag{2.14}$$

Using the cutting behavior in order to lead of a durability of the tool $\mathbf{T} = \mathbf{T}_{op}$ it can be computed the maximum margin.

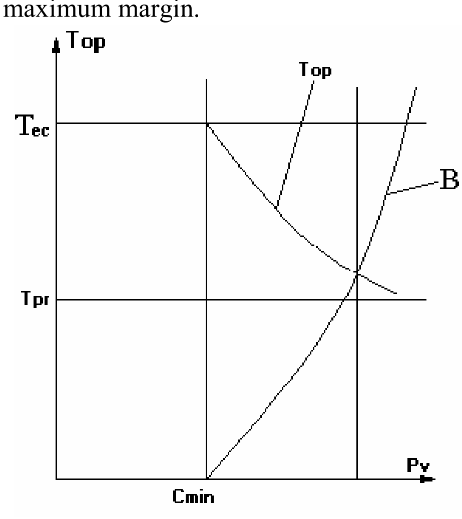


Fig. 2. *The optimum durability chart and the maximum profit B depending on selling price* ***p***

In the figure 2 it is shown the optimum dependence on selling price $\mathbf{p}_v$.

In order to achieve optimum it is necessary firstly to determine parameters characterizing the analyzed system.

Bellow the optimal adaptive control algorithm is described.

Starting with the idea in mind of building an algorithm to incorporate, concerning mathematic point of view, all the elements involved needs to be described coherently the economical technical processes. The algorithm considered:

a) – mathematical model of cutting described by Taylor relation. The direct computation using Taylor formula is difficult, and it is preferred to use the logarithm transformation, for which a process i it is described.

b) – the optimum durability expression it is taking into account technical parameter as well as economical [2.14] it is computed as

$$\mathbf{f}\left(\mathbf{t}_{opt}\right) = \mathbf{T}_{opt}^{m} - \frac{(1-\mathbf{m})\cdot\mathbf{C}\cdot\mathbf{p}\cdot\mathbf{s}_{max}^{1-x}}{\mathbf{C}_{\tau}}\frac{\mathbf{T}_{opt}-\mathbf{T}_{pr}}{\mathbf{T}_{ec}-\mathbf{T}_{pr}} \quad (2.33)$$

In figure 3 it is described the proposed algorithm. Data acquisition it is performed at every blank processed. Therefore, it is building a database which is computed a pattern to follow to achieve optimization.

System identification by intermediary of parameters from Taylor expression(C, m, x, y) it is performed continuously (excepting first three blanks).

The system is generating advisory concerning cutting parameters changing if any measured parameters alteration occurs. In the cutting process control we must to consider the following important aspects:

- meeting technical characteristics imposed concerning dimensions;
- obtaining the surfaces with the imposed roughness;
- performing the cutting process meeting the condition of economical efficiency.

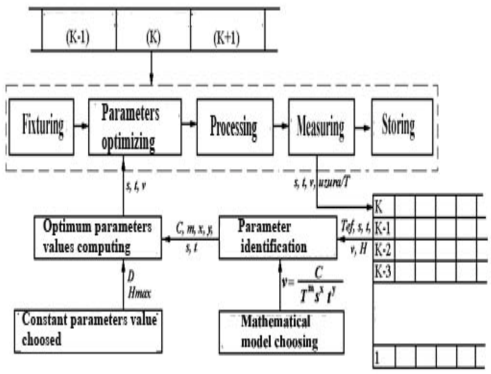


Fig. 3. *Algorithm description*

It is considered one pass cutting process of a part batch. The obtained surface processing must be performed under certain roughness and precision condition. Machining allowance is varying to one blank to another and even one area to another. Besides taking into account of roughness and tolerancing (which are the technical restrictions of optimizing problem) it is compulsory the "on-line" objective function maximizing representing the margin value, for a better global processing economical performance. To achieve this, we must assure that during the processing we continuous change feedrate and cutting speed, to obtain surface quality and objective function maximizing. In the some time, the cutting depth must be continuously changed to achieve necessary accuracy.

To reach an effective optimal adaptive control it is required to use computer automation. A software was build to process data performing acquisition, processing, storing, and computing the calculation. The program developed is performing a continuous identification, suggesting feedrate and working speed to assure an optimal, both under the technical and economical criterion.

The requirements needed were considered in developing of the program as it follows:

- input data to be executed continuously or interrupted as the way processing is designed;
- the requirement to store all data for every test ;
- friendly interface operation, allows user to operate with no special knowledge ;

- both input on real test and virtual test acquisition ;
- database previous test information available for user.

It is considered a batch processing with the changing order frequency equal to that of processing the blank through manufacturing system.

Following the test steps the program is divided as described bellow:

- there are inputted constant data, concerning technical and economical aspects, describing the test ;
- it is considered, in the fist step, the data from previous two steps, when the working parameters used are choosed based on the worker experience;
- after the first step the software is suggesting the feedrate could be used to lead to achieve a surface roughness according to the requirement imposed by the design;
- the some, after the first step of the test are performed the program is suggesting the spindle rotation to obtain the optimum taking into account the highest margin possible ;
- in the following steps the program is using the information from the last four tests, for system identification by computing Taylor parameters.

In the case of noticing the constant behavior of one parameter along more than four test, the phase of data input is suspended as system trend is to stabilize. Furthermore the mathematical model is no longer able to proceed identification. This is the denotive that the process was fully completed In the case of perturbation emergence during processing, the identification phase it is continued until a new stabilizing of the computed parameters.

3. Simulations

In order to analyze the effects of the proposed algorithm were performed several test. Simulations were computed following a test program in order to stress the algorithm characteristics and of the software using mathematical model of the afore mention algorithm

We performed both physical ad numerical test. Considering high possibility of achieving results it the authors insisted on the physical ones whereas the numerical test confirmed the viability of the algorithm

Numerical test considered:

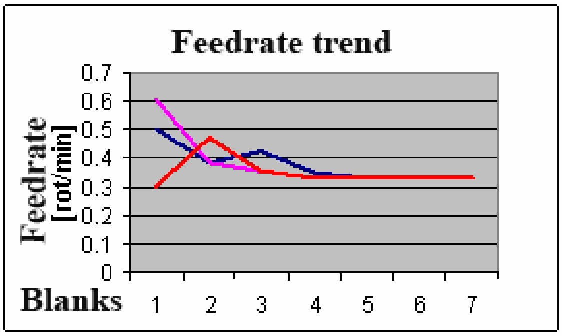
- Behavior study in the case of common cutting conditions;
- Behavior study in the case of the emerging of several input parameters changing (impulse, treapta, economici).

To describe the algorithm steps followed it is presented bellow the results of three test, performed in the some economical conditions, processed for a semi-finishing cutting process. The general economical data, considered for all three tests, are presented in the Figure 4. In figure 5 and figure 6 are shown the data describing first test evolution.

Parameter	um	Symbol	Value
Roughness	microni	Ra	12.5
Blank length	mm	l	800
Reshaping time	min	ta	10
Reshaping cycles	-	nr	16
Tool related cost	lei	Cs	98000
Tool cost	lei	Cas	30%
General costs	lei	Regie	300%
Worker wage	lei	Sl	12000000
Worktime	ore	Ft	172
Adjutment tool time	min	tsr	8
Margin	lei	P	40000
Nominal diameter	mm	Dideal	74.05

Fig. 4. *Data describing first test evolution*

In the figure 5 and figure 6 it is shown the charts variation of the main parameters of cutting process during three consecutive tests depending on index number of blank processed.



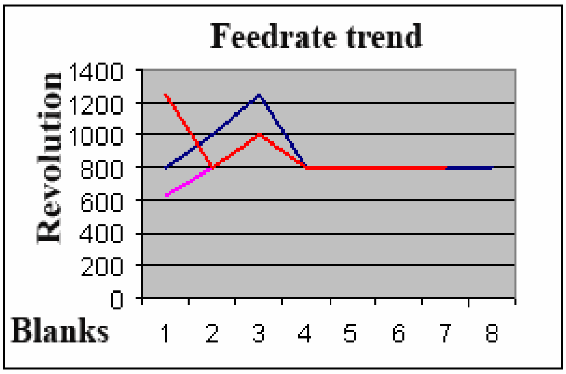


Fig. 5. *Feed rate trend analysis*

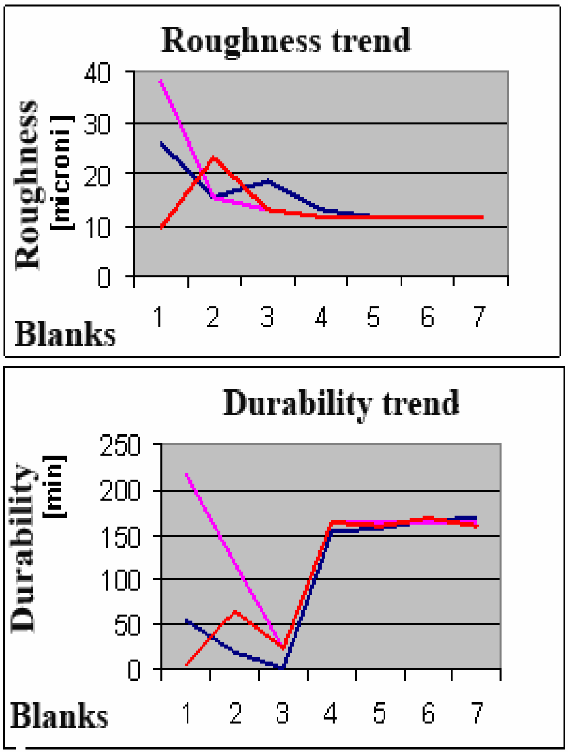


Fig. 6. *Durability trend analysis*

4. Conclusions

The test performed allows a evaluation of the proposed algorithm as well the defining the allowable limits for the software. Several conclusion were asserted::

- both on numerical test and physical test, the optimum parameter values does not depend on the initial parameters;
- if any unit step signal is emerging the program is performing accordingly, achieving identification "on-line" after a small number of blanks, the new values for the technological system This is computed according to the changing of material characteristics of the batch processed;
- the emerging of perturbation it is very well handled by the algorithm, the optimum parameters values are stabilized. This is the case when the material of current blank is very different compared to the previous ones.;
- it was notices that there is a minimum precision of measuring wear which this "on-line" identification is able to compensate. This parameter depends on the cutting process behavior and the cut depth.
- numerical simulation of the adaptive optimal control in the case of the manufacturing system with the both continuous and uncontinous gear changing show that the proposed algorithm is working very well allowing cutting parameters optimizing;
- numerical simulation underlined that the economical parameters are determining the optimal parameters for the cutting process.

Acknowledgement
The authors gratefully acknowledge the financial support of the Romanian Ministry of Education and Research through grant CNCSIS 520/2005.

Bibliography:

1. **Chen Y. S., Yu F.J.**, *Determination of optimal design parameters of mooving average control chart*, Advanced Manufacturing Technology,2003
2. **Freiheit Th., Hu S. J**, *Impact of machimimg parameters on machine reliability and system productivity*, Transaction of the ASME, vol.24, 2002;
3. **Jerard R.B., Fussel B.K., Ercan, M.T.**, *On-line optimization of cutting for NC machining*, Manufacturing&Induastrial Innovation Research Conference, January 2001;
4. **Ko J. H., Yun W. S., Cho D. W., Ehmann F.**, *Development of a virtual machining system,approximation of the size effect for cutting prediction*, International Journal of Machine Tools & Manufacturing, July 2002;
5. **Lan C.H.**, *Optimal control of a multistage machining operation on a computer numerically controlled machine*, Advanced Manufacturing Technology, 2002;
6. **Martin P., Schneider, F., Dantan, J.Y.**, *Optimal adjustmente of a machine tool for improving the geometrical quality of machined parts*, Int J Adv Manuf. Technol. (2005) 26:559-564;

Controlul adaptiv-optimal a maşinilor unelte reconfigurabile

Rezumat

Aceasta lucrare prezintă un algoritm de conducere adaptiv-optimala a procesului de prelucrare bazat pe reidentificarea "on-line" a procesului de aşchiere, considerând drept criteriu de optimizare rata profitului. În acest fel optimizarea procesului de prelucrare tine cont de succesul pe piață al produsului prelucrat. Pornind de la aceste concepte sa realizat unui produs informatic destinat implementării experimentale a algoritmului de conducere adaptiv-optimala a procesului de prelucrare prin strunjire. Este prezentat comportamentul programului numeric in diferite situații de lucru.

Anpassungsfähig-optimale Steuerung der rekonfigurierbar Werkzeugmaschine

Zusammenfassung

Dieses Papier stellt eine optimale adaptive Steuerung des on-line Wiederidentifizierung gegründeten schneidenprozesses. Diese Annäherung zieht in Betracht die optimierenkriterien des Seitenrandes.

Wir betrachten den Markterfolg des verarbeiteten Produktes. Beginnend mit diesem waren Ideen, eine Software, die optimale anpassungsfähige Verarbeitung auf Ausschnitt zu prüfen entworfen.
Auch einiges wurden Simulation durchgeführt, um Algorithmuszuverlässigkeit zu prüfen.