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GLOBAL OPTIMAL CONTROL OF MACHINING OPERATIONS

BY

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Abstract. Nowadays approach regarding machining operations lies on a part-program, depending on the particularities of the process to be run and including needed information about both machined part geometry and process technology. This paper makes a step forward, by developing the concept of global optimal control of machining operations. The control works by firstly dividing the machining operation in a high number of optimization sequences, and then adopting for each sequence the optimal cutting speed. This is made by selecting the mathematical model of the cutting speed and by inputting in it the cutting force medium value and the cutting force variation amplitude (online monitored). A control loop followed after each optimization sequence enables to establish the current optimal cutting speed. In this way, the cutting speed value is permanently adapting to an optimal level, according to a selected form of the optimization model.

Key words: global optimal control, optimization sequence, cutting force monitoring, optimal cutting speed, stability restriction.

1. Introduction

Programming the machine tools on such a manner as they perform the machining operations in optimal conditions was always one of the most

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important targets for those involved in manufacturing area. This is the reason of the huge number of researches dedicated to this problem, by diverse approaches. The differences between these approaches, at conceptual level, are mainly regarding the optimization target (the objective function definition), the manipulated variables choice, or the method used for solving the optimization problem. As optimization criterion, the manufacturing cost (Yang et al, 2011, Costa et al, 2011), the metal removing rate, MRR (Rao & Pawar, 2010, Kurt & Bagci, 2011), the manufactured surface roughness (Neeli et al, 2012), the cutting force magnitude (Farahnakian et al, 2011) or the energy efficiency of the manufacturing process (Bi & Wang, 2012) should be mentioned. There are also present multi-criteria approaches, combining two or three among previously mentioned criteria (e.g. Zhang & Ding, 2013).

A significant drawback of current approaches is their passive character, meaning that once the optimization problem solved, the machining system is set (programmed) to work according to the found solution no matter of what is happening during the machining operation.

2. Problem Formulation

The "traditional" way of programming the machine tool cutting regime (the cutting speed, *v*, the cutting depth, *t*, and the feed rate, *s*), regarding a given operation, lays on using values established before effectively starting the cutting process. We should also notice that in many cases, the only one of the three parameters that may be more freely chosen is the cutting speed, the other two being imposed / limited by technological reasons – e.g. the thickness of material layer to be detached, the generated surface roughness, etc.

In reality, the machining system characteristics may suffer (sometimes important) changes, under the action of variable mechanical / thermal fields, occurring during the process. At the same time, the relative position between the machining system elements is permanently changing during operation ongoing, while diverse perturbations may intervene in any moment. Therefore, it is a mistake to speak about precise, optimum values of the cutting regime parameters for an entire operation. In fact, we might accept this only for very short (elementary) process sequences.

In this paper, we present a new concept concerning the optimal control of the machine tool operation, which should answer to at least two essential requirements:

- The cutting speed must be kept at an optimal level during the entire operation ongoing, no matter the changes affecting the machining system.
- The machining operation control has to be extended to more attributes characterizing the cutting process performance (productivity, stability, dimensional precision etc.), becoming global.

3. Proposed Approach

Let us consider, for example, the case of a turning operation. The current approach regarding operation planning supposes to choose, from the beginning, the desired cutting regime (it is not relevant to talk, here, about how making the choice). The lathe control system is then programmed to perform the operation, by keeping this cutting regime unchanged.

Instead of that, we suggest the following new approach:

- The operation is divided into a high number of optimization sequences. Each sequence will include a given number of cutting cycles (here - worked piece rotations), constant or variable. If we consider a reference worked piece axial section, we can find in it the points on the worked piece corresponding to each cutting cycle (Fig. 1).

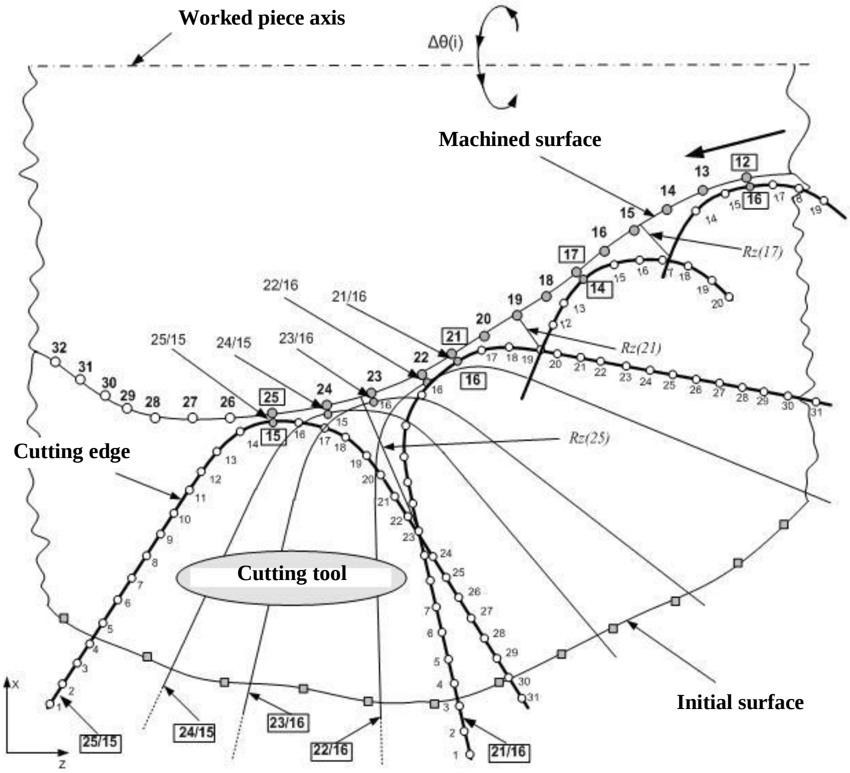

Fig. 1 − The operation division in sequences (Marin, 2009)

The consecutive points whose current numbers are framed (e.g. 12, 17, 21, 25) are delimiting the optimization sequences. In these points, the cutting tool position is also represented.

- The cutting regime parameters are set, only for beginning the first sequence, to an appropriate value, from a database (according to the concrete situation) and the operation starts.

- After each sequence, the machining system behavior is (re)assessed through the analyze of the cutting force evolution (this supposing, obviously, the cutting force online monitoring). The cutting regime (at least the cutting speed) is then modified, in order to fit in with the current situation. This couple of actions is recurrently repeated until the operation finish.

Regarding the problem of cutting regime optimization after each sequence, the following formulation is considered here: we are looking for an optimal value of the cutting speed, as control variable, while the feed rate and the cutting depth values are set under the applied restrictions, concerning the machined surface precision/quality and the machining system loading capacity. A special remark needs to be made about the cutting process stability restriction, to which the optimal cutting speed choice must be submitted after each sequence.

The optimization criterion is usually economical, hence the specific profit rate (*SPR*), meaning the profit rate brought by the machining operation relative to the removed material volume, may be chosen as objective function. According to Frumuşanu & Epureanu, 2015, it has the following expression:

$$SPR = \frac{P_s - C_s}{\left[1 + k + \frac{\tau_{sr}}{T}\right] \cdot \frac{1}{v \cdot s \cdot t}} \quad \text{[Euro/min]}. \tag{1}$$

In relation (1), P_s means the operation specific price, C_s – its specific cost, k – the ratio between the auxiliary time and the machining time, τ_{sr} – the time for worn tool changing, T – tool durability.

Regarding the specific cost, according to the same source, it can be assessed with the formula:

$$C_s = \sum_{i=i}^{n} \left(\frac{Q_i}{T_i} \right) \cdot \left[1 + k + \frac{\tau_{sr}}{T} \right] \cdot \frac{1}{v \cdot s \cdot t} + \frac{\tau_{sr} \cdot c_\tau + c_s}{T \cdot v \cdot s \cdot t} + \frac{c_\tau}{v \cdot s \cdot t} + c_m + \frac{k_{energy} \cdot c_{energy}}{v \cdot s \cdot t}, \quad \text{[Euro/cm}^3\text{]}. \tag{2}$$

The first term from relation (2) reflects the specific cost fraction issued by the use of the needed assets (having the Q_i values and T_i life cycle lengths). The second term gives the share of the cutting tool cost, while the third one refers to the wage cost. The last two terms are related to the specific cost of the detached material and to the consumed energy cost, respectively. In addition to the already specified notations, we have: c_τ - the wage specific cost, c_s - the tool expenditure between two consecutive tool changes, τ_{sr} - the time for worn tool changing, c_m - the specific cost of the detached material, k_{energy} - the energy coefficient, c_{energy} - the energy price.

The global optimal control is intended to be performed on the base of the cutting force online monitoring. Because it should be sensitive to the cutting depth variation (accidental or not), in relations (1) and (2) the cutting depth value will be replaced by the one calculated with:

$$t = \left(\frac{\overline{F}}{k_F \cdot s^{y_F}} \right)^{\frac{1}{x_F}}, \tag{3}$$

relation resulted from the well known Taylor formula. Here $\overline{F}$ is the cutting force medium value, calculated for the last completed cutting sequence, while k_F, x_F and y_F are the specific values of the coefficient/exponents from Taylor formula, in the considered operation case.

It should be noticed that the tool durability can be calculated depending on the cutting regime parameters, so it is not an independent variable in relations (1) and (2). Therefore the objective function (1) may be regarded as $SPR = SPR(v)$. The cutting speed optimal value can be found by maximizing (1), with the help of a numerical application.

The restrictions imposed by machining system technical limitations can be directly applied to the theoretical optimal solution. A special discussion needs to be made relative to the stability restriction, because we know this restriction is satisfied for a cutting speed value only after working with it. The solution that we found is presented in graphical form in Fig. 2.

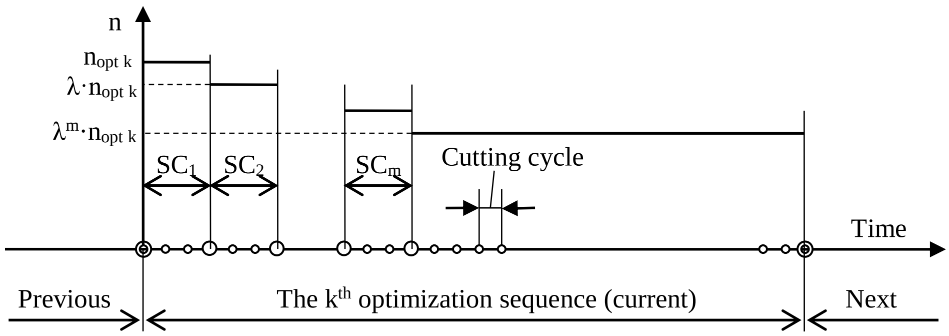

Fig. 2 – The stability restriction implementation

Each optimization sequence starts by setting the rotation speed to the value corresponding to the new optimal cutting speed. Then, a number of stabilization cycles (SC_1, SC_2 ... SC_m) are successively performed. Such a cycle, including several cutting cycles, consists in: *i)* monitoring the cutting force variation, *ii)* calculating, on this base, an indicator reflecting the machining system tendency to become unstable, *I*, *iii)* comparing the indicator value to a limit one I_M and, if necessary, *iv)* adjusting the rotation speed, by applying a sub-unitary coefficient λ to its current value. The stabilization cycle is repetitively applied until the system becomes stable, the rest of the optimization sequence being performed with the cutting speed value resulted after the last necessary stabilization cycle (see also Fig. 3).

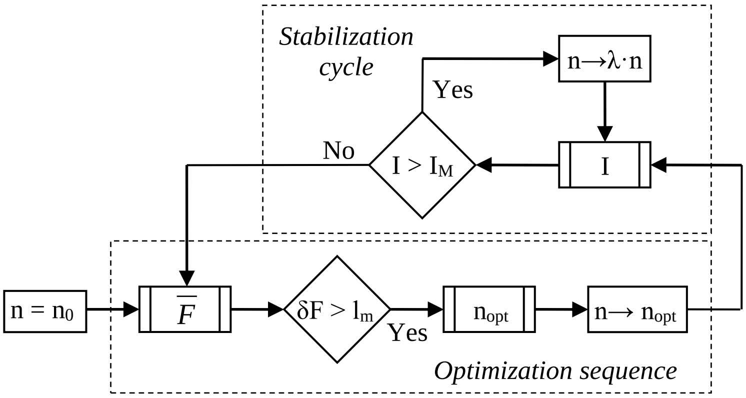

Fig. 3 – The global optimal control principle of application

For a better understanding, the global optimal control application is illustrated in Fig. 3. By δF we mean the relative variation of the medium cutting force, calculated after each optimization sequence, while l_m is a threshold value which, once surpassed, shows the opportunity of adjusting the cutting speed.

4. Numerical Simulation

We further present a numerical simulation, having as purpose to reveal the potential performance brought by the implementation of the global optimal control approach. The case of turning a cylindrical piece of 70 mm diameter, from regular steel with 0.45 % carbon (C45) was considered. The thickness of the material layer to be detached was variable between 0.7 and 3 mm (for a better relevance of the results), while the feed rate was kept constant, at 0.2 mm/rot. The cutting force was online monitored, see Fig. 4.

A cluster of cutting force values, corresponding to 55 piece rotations, was then extracted from the measured dataset and divided into 11 optimization sequences. The medium cutting force value was calculated for each sequence, the results being presented in Table 1.

The optimal cutting speed and the corresponding *SPR* have been calculated for each sequence, by using a MatLab application, developed on this purpose. Their values are also specified in Table 1.

The values of the main input parameters from formulas (1) – (3) were: k = 1, P_s = 1 Euro/cm^3, c_s = 20 Euro, τ_{sr} = 10 min, c_τ = 0.45 Euro/min,

c_m = 0.02 Euro/cm^3, k_{energy} = 15 Wh/min, c_{energy} = 0.23 Euro/KWh, k_F =279, x_F = 1 and y_F = 0.75.

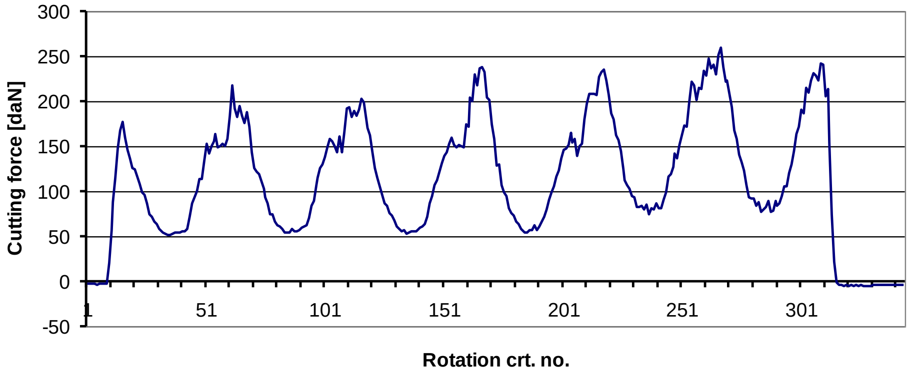

Fig. 4 – The cutting force variation

Table 1
Numerical simulation results

Sequence crt. no.	Medium cutting force [daN]	Optimal cutting speed [m/min]	Maximum *SPR* [Eurocents/min]
1	237.97	115.23	2.94
2	157.85	119.21	1.70
3	95.26	123.84	0.69
4	62.96	127.12	0.15
5	56.49	127.96	0.02
6	65.72	126.78	0.20
7	105.87	122.89	0.87
8	147.87	119.83	1.54
9	150.18	119.70	1.58
10	207.78	116.56	2.48
11	235.75	115.31	2.91

The simulation results show a *SPR* increase with 11.2 %, from the value of 13.56 Eurocents/min (calculated in the case of running the entire operation with constant cutting speed, determined in traditional manner), to the value of 15.08 Eurocents/min (resulted from summing the values of all sequences), when applying the new approach.

5. Conclusions

In this paper, a novel concept namely the global optimal control of the machining operations is presented. It is based on dividing the processes in optimization sequences and it works by cutting force monitoring. The objective function, namely the specific profit rate, to be maximized is more comprehensive than the ones used in the current approaches concerning the manufacturing optimization problem. The results obtained by running a numerical simulation sustain the opportunity of implementing the new concept.

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CONTROLUL GLOBAL OPTIMAL AL OPERAŢIILOR DE PRELUCRARE

(Rezumat)

Lucrarea de faţă prezintă o nouă abordare conceptuală a controlului operaţiilor de prelucrare, bazată pe descompunerea acestora în secvenţe de optimizare şi stabilirea unei viteze optimale pentru fiecare astfel de secvenţă. Controlul propriu-zis se exercită pe baza monitorizării on-line a forţei de aşchiere, atât ca valoare medie, cât şi ca mod de variaţie. Se propune, de asemenea, utilizarea unui criteriu sintetic de optimizare – rata specifică a profitului, în locul criteriilor tradiţionale (productivitate, cost, etc.).