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An Expert Mill Cutter and Cutting Parameters Selection System incorporating a control strategy

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Abstract: In this paper, remove material processes are taking into account for developing an expert mill cutter and cutting parameters selection system based on numerical methods of performance evaluation. The knowledge base is given by limitations in process variables, which let us to define the allowable cutting parameter space. The mentioned limitations lead to instabilities limitations due to tool-work-piece interaction, known as chatter vibrations. The power available in the spindle motor and milling force control restrictions are also considered as process limitations. Besides, an additional term is taken into consideration in order to be sure of avoiding chatter vibrations when the programmed spindle speed varies due to spindle deflections or perturbations. Then, a novel tool cost model is contrived. It is used to choose a suitable tool, among a known set of candidate available cutters, and to obtain the appropriate cutting parameters in an optimal way. Once the tool and the cutting parameters are obtained, the developed system is able to redefine the cutting parameters automatically if new considerations about machinery data are required through expert rules. Such optimal cutting parameters can be obtained by manipulating the cost function weighting factors. An example is presented in order to illustrate the method.

1. INTRODUCTION

This paper bring forward the concept of selecting an appropriate mill cutter, among a known set of candidate cutters, while obtaining the adequate cutting parameters for milling operations through an expert system. The developed expert system consists of the relative compliance between the tool and the work-piece. It is predicted with analytical methods, previous knowledge of tool and work-piece modal characteristic and material properties. First, the allowable cutting parameter space for each available cutter, restricted by milling process constraints is obtained. Then, a cost function is designed, it is composed by four terms, power consumption, material remove rate (MRR), a stability margin in order to avoid possible perturbations in the spindle speed and tracking error performance of the adaptive control of milling forces. A weighting factor measures the importance of each term in the cost function. The values of the cutting parameters of each tool are evaluated in the cost function, obtaining the tool and cutting parameters which minimize this cost function, for a given weighting factors. The weighting factors measure the process requirements, i.e the amount of material to be removed, the power consumption, the robustness stability against possible perturbations in the spindle speed and the output tracking error signal. Moreover, the expert system is able to modify automatically the weighting factors in order to refine production requirements and then, programming successfully new cutting parameters which lead to desired production objectives.

2. SYSTEM DESCRIPTION

The standard milling system can be modelled as a second order differential equation excited by the cutting forces, $F(t)$, (Balachandran, 2001, Insperger et al., 2006)

$$M\cdot\ddot{r}(t)+B\cdot\dot{r}(t)+C\cdot r(t)=F(t) \qquad (1)$$

where $r(t)=\{x(t)\quad y(t)\}^T$ are the relative displacements between the tool and the working-piece, $F(t)=\{F_x(t)\quad F_y(t)\}^T$, and M, B and C are the modal mass, damping and stiffness matrices. The milling cutting force is represented by a tangential force proportional with the instantaneous chip thickness, and a radial force which is expressed in terms of the tangential force (Altintas, 2000, Balachandran, 2001, Insperger et al., 2006).

The most critical variable in the equation of motion, the chip thickness-$t_c(t)$, consists of a static part and a dynamic one. The static's is proportional to the feed rate, and it is attributed to the rigid body motion of the cutter. The dynamic one models two subsequent passes of the tool through the same part of the work-piece (Altintas, 2000, Balachandran, 2001, Insperger et al., 2006),

$$t_c(t)=f_r\cdot\sin\phi_j+\left[x(t-\tau)-x(t)\right]\cdot\sin\phi_j+\left[y(t-\tau)-y(t)\right]\cdot\cos\phi_j \qquad (2)$$

where f_r is the feed rate, ϕ_j the immersion angle and τ is the delayed term defined as $\tau=\frac{60}{N_t\cdot S_s}$, N_t is the number of teeth and S_s the spindle speed.

The equation of motion (1 and 2) corresponds with a second order delay differential equation with time varying parameters. It can be solved numerically (Insperger and Stépán, 2002, Bayly et al., 2003) or analytically (Budak and Altintas, 1998). The solution of the equation in the parameters space (axial depth of cut and spindle speed) yields to the stability lobes charts (Stépan, 1989, Budak and Altintas, 1998) which gives the pairs axial depth of cut and spindle speed for which the system does not acquire undesirable chatter vibrations.

Once the vibratory problem has been stated, uncertainties in the cutting process, the force-feed nonlinearity inherent in the metal cutting process, and machine requirements, such as avoid tool breakage or not damage machine components, can be accommodated using a control strategy (Kurdi, M.H, 2005). The control strategy is aimed at maintaining a constant level of cutting force. A successful application of the control to milling process has potential machining times saves among other advantages (Altintas, Y. and Ma, C.C.H, 1990).

Then, a continuous transfer function which relate both signals, measured resultant force and the actual feed delivered by the drive motors can be modelled as a first order dynamics (Altintas, 2000), in chatter and resonant free zones. At the same time, the relationship between the machine tool control, the Computerized Numerical Control (CNC), and the motor drive system can be approximated as a first order system within the range of working frequencies (Altintas, 1992, Altintas, 2000). This transfer function relates the actual, f_a, and the command, f_r, feed velocities.The combined transfer function of the system is given by (3),

$$G_c(s)=\frac{F_p(s)}{f_c(s)}=\frac{K_p}{(\tau_s s+1)(\tau_c s+1)} \text{ (6), with } K_p\left(kN\cdot s/mm\right)=K_c a_{dc} r/N_t S_s$$

where $K_c\left(N/mm^2\right)$ is the resultant cutting pressure constant, $a_{dc}(mm)$ is the axial depth of cut, $r(\phi_{st},\phi_{ex},N_t)$ is a non-dimensional immersion function, which is dependent on the immersion angle and the number of teeth in cut, N_t is the number of teeth in the milling cutter, $S_s(rev/s)$ the spindle speed , $\tau_c = 1/N_t S_s$ and τ_s an average time constant.

3. KNOWLEDGE BASE

Milling processes basically consist of two phases, roughing and finished the surface (Kim, S. 2006). In this paper milling roughing processes are analysed. They are based on removing the maximum amount of material or metal from a work-piece while avoiding damage machine components and the breakage of the tool. The main drawback, when large amount of material is removed, is the ability of the system to acquire vibrations which limit the productivity of the process. These vibrations are known as chatter, they are typically modelled by the equation (2), and resolving (1) and (2) in the parameter space the well-known stability chart is obtained. On the other hand, , machine tool components and the tool are desired to be preserved of damaging or breakage using, in this case, an adaptive control algorithm, the reasons of using this kind of control are uncertainties and the nonlinear behaviour of the milling system. Moreover, machine tool constrains, such as, the maximum power available from spindle drives (Altintas, Y. 2000) is also taken into consideration in order to design the expert system.

The developed expert system consists of a series of rules which are classified into three types, preliminary, optimization and expert rules. The preliminary rules are defined in order to take into consideration approximations when constructing the stability charts and to add more robustness to the milling system, as well as they define the input cutting parameter space given by vibration, spindle power and control restrictions . In addition, the optimization rules give us the tool and the cutting parameters based on a cost function built from the set of preliminary rules. Finally, the expert rules modify the initial weighting factors automatically if new constraints are required for the process. Moreover, the used weighting factors are saved and stored for utilizing them when planning future work in easier way for machining operators.

3.1 Preliminary rules

These rules have been designed to take into account approximations when calculating analytically the stability charts (Budak and Altintas, 1998, Altintas, 2000). Then, the following algorithmic methodologies are used as *preliminary rules* of the knowledge base,

Rule 1: Stability robustness.

Rule 1.1: The stability lobes are calculated from a linear approximation (Budak and Altintas, 1998), so that the nominal stability frontier and its neighborhood are inaccurate as stable regions of the real nonlinear problem. For this reason and in order to calculate secure stability lobes char, a small accurate stability margin is prescribed, i.e, it is supposed that the chatter vibrations happen at $\delta+i\cdot\omega_c$ $(\delta>0)$ instead of at $i\cdot\omega_c$ when the stability border line is calculated.

Rule 1.2: The expression of the value of axial depth of cut which limits stable and unstable zones is multiplied by a factor, α , $0<\alpha<1$, aiming at improving the robustness of the system when the lobes charts are calculated. Then, a confine on this parameter, $a_{dc,\lim}=\alpha\cdot a_{dc,\lim}$, lets a better control capacity in the spindle speed, but limiting the amount of material to be removed.

Rule 2: Allowable cutting space parameter.

Rule 2.1: The value of pair, axial depth of cut and spindle speed, which compose the border line between stable and unstable zones, satisfying rule 1 is calculated.

Rule 2.2: The admissible input space subject to control and spindle motor power availability constrain, is obtained. In this subsection control restrictions and spindle power availability constraints are explained in detail.

3.1.1 Control restrictions

During machining, maintaining a constant level of cutting force is desirable because excessive cutting forces cause the breakage of the tool or damage machine components. Furthermore, variation in cutting force may result of spindle or work-piece deflection, thus deteriorating the geometry on the work-piece. Then, the programmed feed rate is restricted by control constrains (Rober et al. 1997).

The continuous transfer function, eq. (6), is discretized under a zero order hold (ZOH),

$$H(z)=Z\left[\frac{1-e^{-sT}}{s}\cdot G_c(s)\right]=\left(1-z^{-1}\right)\cdot Z\left[\frac{G(s)}{s}\right]. \quad (4)$$

The continuous model reference system is chosen to be a typical second order plant with $\xi=0.75$ and $\omega_n=\frac{2.5}{4\cdot T}$, where T is the sampling period.

For this aim, model reference adaptive control is applied where recursive least square estimator updates the estimation parameter vector. The aim of the model-following control strategy is to force the closed loop system to behave as a prescribed reference model. (Rubio et al. 2007).

3.1.2 Spindle Power availability constraints

The power draws from the spindle motor constraints the machining efficiency. It is found from (Altintas, 2000, Maeda et al. 2005),

$$P_t=\pi\cdot D\cdot S_s\cdot\sum_{j=1}^{N_t}F_{tj}\left(\phi_j\right) \quad (5)$$

where D is the tool diameter, S_s the spindle speed and F_t the tangential cutting force. The maximum cutting power, $P_{t\max}$, required for the spindle motor is the maximum value among the instantaneous power P_t in one tooth period, $P_{t,\max}=\max\left(P_t\right)$ (Maeda et al. 2005).

3.2 Tool and cutting parameters selection

The aim of the paper is to select a tool among available ones. Once the tool has been selected, adequate cutting parameters are required. In this section, an approach for tool and cutting parameters selection is suggested in this way. It is based on a designed cost model function and the explained below optimization rules. Each candidate tool is characterized by the following set of parameters:

$$R_i=\left(\omega_{nxi},\omega_{nyi},\xi_{xi},\xi_{yi},k_{xi},k_{yi},N_{ti},D_i,\beta_i\right) \quad (6)$$

where the pairs $\left(\omega_{nxi},\omega_{nyi}\right)\in\omega$, $\left(\xi_{xi},\xi_{yi}\right)\in\xi$ and $\left(k_{xi},k_{yi}\right)\in k$ represent the tool natural frequency, damping ratio and static stiffness, respectively, and N_{ti},D_i and β_i characterize the number of teeth, the diameter and the tool helix angle. $R_i\in T^o$, $i=1,2,..n$, being n the number of tools and T^o the set of tools available to the designer. ω,ξ and k represent the set of tools′ natural frequencies, damping ratio and static stiffness for each tool.

3.2.1 Tool cost model definition

A novel cost function has been conceived in order to carry out the selection of a suitable tool and cutting parameters. The tool cost model for a single milling process can be calculated using the following equation, (7):

$$C\left(P_t,MRR,\Delta S_s,e_t;R,c_{i(i=1,2,3,4)}\right)=c_1\cdot NF_1\cdot P_t+c_2\cdot\frac{NF_2}{MRR}+c_3\cdot\frac{NF_3}{\Delta S_s}+c_4\cdot NF_4\cdot e_t$$

The function has four terms. Each term is composed by a weighting factor (c_i), a standardization factor (NF_i) and parameters which limit the process efficiency. These parameters are MRR, power consumption, a range against possible perturbations in tool rotational motion, and error tracking. The tool cost function is designed to be MRR, power consumption, a range against possible perturbations in tool rotational motion, and error tracking dependent, at the same time it is designed to be inversely proportional to MRR and a range against possible perturbations and directly to power consumption and error tracking. These parameters play an important role when selecting cutting parameters since them measures how well the process goes on. They take the following definitions:

The MRR measures the amount of material removed from the working piece. It is an index use as referee to indicate the performance of the process in roughing milling processes. The $MRR=a_{dc}\cdot r_{dc}\cdot f_c$, where a_{dc} is the axial depth of cut, r_{dc} the radial depth of cut and f_c the feed velocity.

The cutting power draw from the spindle motor is a major constrain of the machine tool technology, it is defined as $P_t=V\cdot\sum_{j=1}^{N_t}F_{tj}=\pi\cdot a_{dc}\cdot D\cdot\sum_{j=1}^{N_t}F_{tj}$, where a_{dc} is the axial depth of cut, D the diameter of the tool and F_t the tangential force.

The tracking error signal, e_t, give us a measurement of how the system follows the reference one. Better tracking means avoid the breakage of the tool, maintain the forces below a prescribed safety upper bound which can lead to damage critical machine tool components, and tracking a constant reference, since variation in the cutting force may result in a variation of spindle or work-piece deflection, thus deteriorating resultant geometry accuracy.

An additional term, spindle speed security change, ΔS_s, is added to the cost function model in order to be sure avoiding chatter vibrations when the spindle speed is varied due to spindle deflections or perturbations. It measures the nearest spindle speed at which chatter vibration happen. This fact allows having an error margin due to possible perturbation in this variable. This parameter has been defined by the authors yet in previous paper, due to extension problems, here this paper is referred to follow the definition (Rubio et al., 2006).

The weighting factors add one $\left(\sum_{i=1}^{4}c_i=1\right)$, they measures the importance of each term in the cost function. The standardization factors (NF_i), $i=1,..,4$, equalize the magnitude order of each term in the cost function. They are defined as follow, $NF_1=P_{t,av}^{-1}$, being $P_{t,av}$ the power available in the spindle motor, $NF_2=MRR_{\max}$, where $MRR_{\max}$ is the maximum

MRR which is achieved among all the candidate cutters, $NF_3 = \Delta S_{s,\max}$, $\Delta S_{s,\max}$ is the maximum measured value of this variable taking into account the candidate tools, and the same for the maximum error tracking, $e_{t,\max}$.

3.2.2 Optimization rules

The above defined tool cost function has been defined in order to select appropriate tool and cutting parameters by selecting an optimal operating point. The selection of pairs, tool and operating point, is performed in a integrated way through the following optimization rules:

Rule 3: Weighting factors selection.

The weighting factors $c_i, i = 1,..,4$ are intended to be programmed by the machine operator and have the restriction to sum one. Since this paper is referred to roughing milling processes, it is a priority the amount of material to be removed. On the other hand, machine tool physical constraints, such as spindle power consumption or the maintenance of tool and machine components is of paramount importance to minimize cost. An optimal trade-off between requirements and limitations will optimize the process. In any case, the expert system will incorporate an automatic selection of the c_i -parameters according to required specifications.

Rule 4: Tool selection criterion

In order to select an adequate tool, a simple criterion has been followed. For a given values of c_i , and a given tool characteristics, the value of the cost function is saved for all the admissible input cutting parameter space and the minimum value is obtained. The procedure is repeated for all the available cutters. Comparing the minimum value of the cost functions for all available or candidate cutters the corresponding cutter to the minimum value of the minimum value of the cost function, is the selected tool.

The selection criterion is mathematically expressed as, **compute**, $C\left(P_{t,j}(q_j), MRR(q_j), \Delta S_{s,j}(q_j), e_{t,j}(q_j); R_k, c_i\right)$ **for each** $R_k \in T$ **,** $k \in \overline{N}$ **,** being $\overline{N}$ the set of candidate tools and $\forall q_j \equiv \left(S_{s,j}, a_{dc,j}, f_{r,j}\right) \in Q$ where $j \in \overline{N}_p = \{1,..,N_p\}_p$; $p \in \overline{N}$ (denoting that each machine can be potentially tested for different operating points) is a discrete subspace of the cutting parameters space where the cost function is calculated.

For obtaining the selected tool, ST , **compute** $ST = \arg\min_{i \in N} \left\{C\left(P_t(q_j), MRR(q_j), \Delta S_s(q_j), e_t(q_j); R_k, c_i\right)\right\}$, with $ST \in T$, obtaining the appropriate tool according to the criterion. Following the rules, the expert system provides an appropriate tool among the candidates.

Rule 5: Cutting parameter selection

Rule 5.1: Once the tool has been selected, the cutting parameters are the values of S_s, a_{dc} and f_r corresponding to the minimum value of the cost function for the selected tool and the required values of the c_i parameters. It is expressed mathematically as follow (8),

$$q^* = \left(S_s^*, a_{dc}^*, f_r^*\right) = \arg\min_{q_j \in Q} \left\{C\left(P_t(q_j), MRR(q_j), \Delta S_s(q_j), e_t(q_j), ST, c_{i(i=1,..,4)}\right)\right\}$$

obtaining an input cutting parameter for the selected tool. In this case it is recommended the use of standardizing factors obtained by the selected tool in the cost function, in order to obtain more precise results. In this case the normalization factors are obtained only using the selected tool, without taking into account the discarded tools.

Rule 5.2: In order to have a more accurate possibility, it has been taken into consideration that the cutting parameters can be searched with a more fine integration step around the point

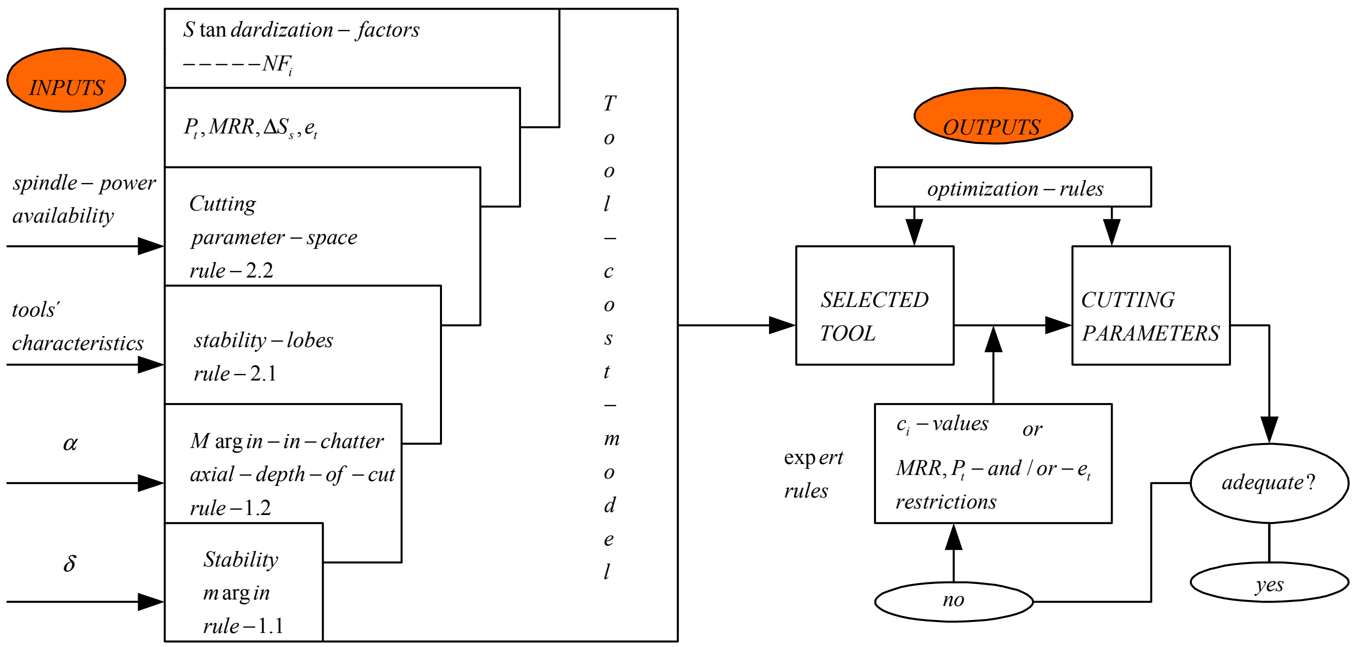

Fig. 1: Schematic representation of the expert system

where the cost function gives its minimum value. In this case, the cutting parameter space is given by a 3-tuple $Q^* = \left(S_s^{*(k)}, a_{dc}^{*(k)}, f_r^{*(k)}\right)$ around q^*, for $k=1,..,p$, where p is the number of points to be considered, according to rules 1 and 2. The procedure for obtaining the required cutting parameters is the same as used in Rule 5.1 through equation (8) for the above defined new cutting parameters. Mathematically, compute (9),

$$q^{**} = \arg\min_{q^{*(k)}} \left\{ C\left(P_t\left(q^{*(k)}\right), MRR\left(q^{*(k)}\right), \Delta S_s\left(q^{*(k)}\right), e_t\left(q^{*(k)}\right), ST, c_{i(i=1,..4)}\right)\right\}$$

Rule 6: Tuning c_i values to prevent process malfunctions

Nevertheless, in programming the selected tool and cutting parameters, malfunctions of the process may lead to poor behaviour of the process, mention, for example, tool wear or burr formation. These phenomena, which are common in manufacturing processes, make that the analytical and experimental testes are not always in concordance. If it is the case, the following algorithmic methodology could be applied,

while $A_{chatter} > A_{tooth-pass}$, $c_2 \leftarrow 0.99 \cdot c_2$, $c_3 \leftarrow 0.01 \cdot c_2 + c_3$ **end**

where $A_{chatter}$ is the chatter frequency vibration amplitude, and $A_{tooth-pass}$ is the highest amplitude among the tooth passing frequency and its harmonics.

3.2.3 Expert rules

Rule 7: Automatic rule of weighting factors modification

In order to achieve certain process or machine tool requirements in the cost function variables, the c_i parameters are automatically redefined in the following way: $J = \sum_i c_i \cdot J_i$ represents the proposed cost function of the equation (10). For a given operation, **if** $k = \dot{k}_o = l \cdot k_o$, $l \in N$ and $\underline{J_i} \le J_i \le \sigma_i \cdot J_i = \overline{J_i}, \sigma_i > 1$, **then if** $\sum_{k_o(l-i)}^{k_o l} J_i > \sum_{k_o(l-i)}^{k_o l} \overline{J_i}$, $c_i \leftarrow \left(1+\rho_i \frac{\overline{J_i} - J_i}{\overline{J_i}}\right) \cdot c_i$, **else if** $\sum_{k_o(l-i)}^{k_o l} J_i < \sum_{k_o(l-i)}^{k_o l} \underline{J_i}$, $c_i \leftarrow \left(1+\rho_i \frac{J_i - \overline{J_i}}{\overline{J_i}}\right) \cdot c_i$ **end**.

Rule 8: Weighting factors renormalization.

It is needed to renormalize the weighting factor aimed at adding one $\left(\sum_{i=1}^{4} c_i = 1\right)$. Two possibilities are taken into account:

1. $0 < \bar{c} \leftarrow \sum_{i=1}^{4} c_i$, $c_i \leftarrow c_i / \bar{c} \Rightarrow \sum_i c_i = 1$.

2. $c_i + \Delta c \leftarrow c_i$ and $c_{i'} - \Delta c \leftarrow c_{i'}$ for $i, i' = 1,..4$ and $i \ne i'$.

Rule 9: Parameters storage

The c_i parameters and the corresponding cost function variables are saved and stored. A database is created with those values, which relates c_i parameters to process variables in order to keep previous knowledge. This information can be further used for programming initial c_i parameters according with production requirements, training novel operators and search for more accurate cutting parameters.

Figure 1 shows the schematic representation of the expert system.

4. EXAMPLE

For the validation of this method, the above study has been applied for two practical straight cutters and full immersion up-milling operation. The example considers the tools to have the following characteristics, according with notation of the section 3, $R_1 = (603, 666, 3.9, 3.5, 5.59, 5.715, 3, 30, 0)$, and $R_2 = (900, 911, 1.39, 1.38, 0.879, 0.971, 2, 12.7, 0)$. The natural frequency is in hertz, the tool damping in %, the tool stiffness in $KN \cdot mm^{-1}$ and the diameter of the tool in mm. The work-piece is a rigid aluminum block whose specific cutting energy is chosen to be $K_{t,1,2} = 600 KN \cdot mm^{-2}$ and the proportionally factor is taken to be $K_{r,1} = 0.3$, for the tool 1, and $K_{r,2} = 0.07$, for the other one. Other parameters belong to the expert system take the following values, the stability margin factor, $\delta = 0.05$, and the stability margin factor for the axial depth of cut, $\alpha = 0.95$. The analytical testes for mill cutter selection were conducted using spindle speed of 1000 rpm, axial cutting depths started with its minimum value in the stability border line divided by ten, with increments of the same size. It is supposed that the spindle speed guarantees 12745.3 W of power. The resulting tool is that leading to the minimum tool cost function value. In figure 2, it is shown the values of the cost function as c_2, c_3, c_4 parameters varies and c_4 is taken as a constant. This study has been done to illustrate the influence of the c_i parameters in the tool cost function. It is observed that the tool R_1 has a better behavior

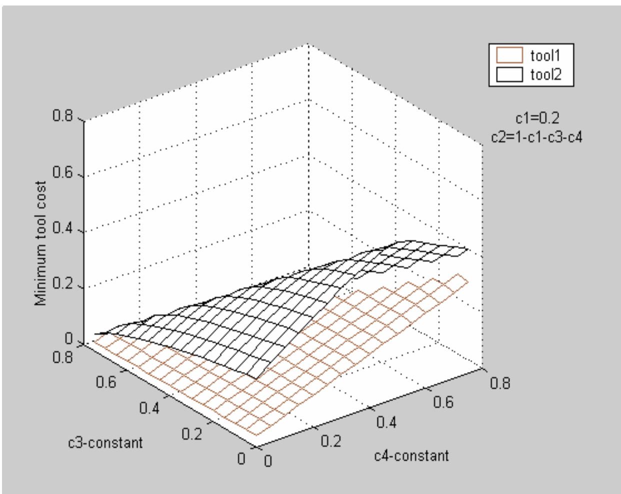

Fig.2: Minimum cost function versus c_2, c_3, c_4 varies and $c_1 = 0.2$

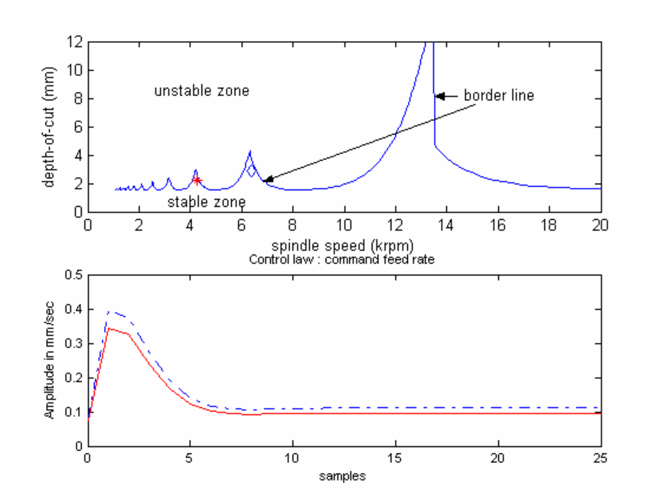

Fig. 3: Situation of the programmed cutting parameters in the lobes chart and programmed feed rates.

respect to the tool R_2 for the all range of the c_i parameters, after studying the simulations varying the c_1 value.

In order to select the cutting parameters, it is supposed that a roughing milling process is running, and the preservation of the tool is required. Then, the following c_i parameters are programmed, $c_1 = 0.05$, $c_2 = 0.5$, $c_3 = 0.05$ and $c_4 = 0.4$, which is equivalent to program $q^{**} = (4250, 2.205, 0.0964)$, using rules 5.1 and 5.2. In this case, the spindle motor power consumption is $8218.3W$, the MRR is $45.1694\, mm^3/s$ and the error 0.1670. But, if it would be desired to increase productivity, in spite of the risk of damaging the tool and/or machine components, due to production requirements. Then, the following c_i parameters could be programmed according to rule 8.2, $c_1 = 0.05$, $c_2 = 0.55$, $c_3 = 0.05$ and $c_4 = 0.35$, given the following cutting parameters $q^{**} = (6400, 2.894, 0.1108)$. In this other case, the spindle power consumption is $12440W$, $MRR = 110.9444\, mm^3/s$ and the tracking error is 0.1779. In figure 3, it is showed the situation on the stability charts of the above programmed cutting parameters and feed velocity, in reds for the case 1 and in blues for the second one. The control signal (feed velocity) is smooth and feasible, and the pairs spindle speed-axial depth of cuts are under the border line in the stable zone and they are situated between two lobes which are places with maximum depths of cut for a constant spindle speed. The c_i parameters obtained are saved and stored in order to create a data base for operator easy work. In this way, the operator only has to program easy c_i values when programming cutting parameters.

5. CONCLUSIONS

An efficient approach for mill cutter and cutting parameters selection has been developed through an expert system. The expert system is instructed with the characteristics of the candidate tools, as well as with the stability margin and constrains of the operation, such as power availability, robust and control requirements. Furthermore, a tool cost function built from a set of expert system preliminary rules, is proposed to evaluate the possible performance of each candidate tool in milling processes. This performance index is then used to select an appropriate tool and cutting parameters for the operation which lead to the maximum productivity, while respecting stability, power consumptions margins and control constraints through optimization rules. Furthermore, the expert system is able to modify the initial value of the weighting factors automatically if new constraints are required for the process. Moreover, the used weighting factors are saved and stored for utilizing them when planning future work in easier way for machining operators. A simulation example which shows the behavior of the system is presented.

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