Rubio Rodriguez, Luis and De la Sen Parte, Manuel

An Expert System for Mill Cutter and Cutting Parameters Selection

Original Citation

Rubio Rodriguez, Luis and De la Sen Parte, Manuel (2005) An Expert System for Mill Cutter and Cutting Parameters Selection. In: Advances in Computer, Information, System Sciences and Engineering. Proceedings of IETA 2005, TeNe 2005 and EIAE 2005 (XVI). Springer, London, UK. ISBN 978-1-4020-5261-3

An Expert System for Mill Cutter and Cutting Parameters Selection

Luis Rubio* and M. De la Sen**
Instituto de Investigación y Desarrollo de Procesos
Facultad de Ciencia y Tecnología, Campus Leioa
Universidad del País Vasco Apdo.644, Bilbao,Spain
* **webrurol@lg.ehu.es** ** wepdepam@lg.ehu.es

***Abstract*—This paper discusses the selection of tools in milling processes. To carry out this research, it has been developed an expert system based on numerical methods. The expert system, chooses an appropriate tool, between a known set of candidate available cutters. The knowledge base is given by limiting the process variables. They are obtained taking into account, instabilities due to tool-work-piece interaction, which are called chatter vibration, and the power available in the spindle motor. Then, a tool cost model is designed as pattern, which is then used to decide the suitable cutting tool. Once the cutting tool is selected, the optimal cutting parameters are calculated. To obtain those parameters other two cost function are designed, which are dependent on the frequency and on time domain output signal properties. An example is presented to illustrate the method.**

Keywords; cutter selection, milling, expert system, chatter.

I. Introduction

Machining, in particular milling operations, is a broad term used to define the process of removing material from a work-piece. Furthermore, the milling operation process planning is required, nowadays, to increase its productivity, reducing cost and improving the final product [1].
This paper brings forward the concept of selecting an appropriate mill cutter, among a known set of candidate cutters, and obtaining the adequate cutting parameters for milling operations through an expert system.

There are several versatile approaches for tool and/or cutting parameter selection based on expert systems on manufacturing environments. Wong and Hamouda [2] developed an on-line fuzzy expert system. The system inputs the tool type, the work-piece material hardness and the depth of cut, and control the cutting parameters at the machine, as output. Cemal Cakir et al. [3] explained an expert system based on experience rules for die and mold operations. In that paper, the geometry and material of the work-piece, tool material, tool condition and operation type are considered as inputs. Then, the system provides recommendations about tool type, tool specifications, work-holding method, type of milling operation, direction of feed and offset values. Vidal et al. [4] focused on the problem of choosing the manufacturing route in metal removal process. They select the cutting parameters by optimizing the cost of the operation taking into account various factors, such as, material, geometry, roughness, machine and tool. Carpenter and Maropoulus [5] designed a system, which provides reliable tool selection and cutting data for a range of milling operations. The method employs rule based decision logic and multiple regression techniques for a wide range of materials. This paper brings forward the concept of scheduling an appropriate cutting tool and the optimal cutting parameters through an expert system for milling processes.

The knowledge base of the expert system is based on numerical methods. The stability-lobes-diagram gives the stability boundary against the chatter vibration. The time domain simulation obtains the outputs variables, for given cutting parameters.

The expert system is instructed with the characteristics of the candidate tools. According to power consumption, chatter vibration avoidance and stability requests, a suitable tool is selected based on a defined tool cost model and selection criterion.

Once, the cutting tool is selected, the cutting parameters are obtained for the given tool configuration. Other cost function is designed. It is composed by the above mentioned cost function and other two cost function, based on time and frequency domain system response. Normally, the weight of those functions is less than the first one. Thus, the expert system selects a tool among the candidates, as well as the appropriate cutting parameters for it.

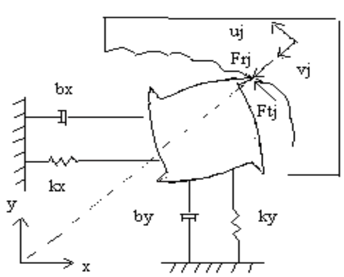

Figure 1. End part of the milling system tool and work-piece

II. SYSTEM DESCRIPTION

It has been developed a milling model, which assumes the cutter to have two orthogonal degrees of freedom and the work-piece to be rigid, as it can be seen in Figure 1.

A. Dynamic model

The dynamic model of the milling cutter is assumed to be a system with one mode of vibration in each direction x and y, while the feed direction is along the x - axis. The milling cutter has n_t teeth, which are equally spaced. The dynamics of the system is given by the differential equations,

$$
\begin{aligned}
m_x \cdot \ddot{x} + c_x \cdot \dot{x} + k_x \cdot x &= \sum_{j=0}^{n_t} f_{xj} = f_x(t) \\
m_y \cdot \ddot{y} + c_y \cdot \dot{y} + k_y \cdot y &= \sum_{j=0}^{n_t} f_{yj} = f_y(t)
\end{aligned}
\qquad (1)
$$

where m_i, c_i, k_i are the mass, damping and stiffness of the model in each direction, f_{xj} and f_{yj} are the components of the cutting force that is applied by the j^{th} tooth, which are obtained by projecting f into the two orthogonal axis.

B. Cutting force model

The cutting force model express the tangential component to be proportional to the instantaneous chip thickness, the axial depth of cut b, and the specific resistance of the material to be removed k_t,

$$F_t = k_t \cdot b \cdot h \qquad (2)$$

The radial component of the force is,

$$F_r = k_r \cdot F_t \qquad (3)$$

where k_r is a proportional constant, $k_t, k_r > 0$.

C. Chip thickness model

The chip thickness is the most critical parameter because not only does it change with the geometry of the cutting tool and the cutting parameters, but also with the uneven surface left by the previous passes of the cutting tool. The resulting instantaneous chip thickness consists of a static part, $s_t \cdot \sin\phi_j$, attributed to the rigid body motion of the cutter, and a dynamic component caused by the vibrations of the tool at the present ν_j and previous tooth period, ν_{jo}. The total chip thickness can be obtained by,

$$h(\phi_j) = \left[s_t \cdot \sin\phi_j + \left(\nu_j^o - \nu_j \right) \right] \cdot g(\phi_j) \qquad (4)$$

where $g(\phi_j)$ is a step function, which determines whether the tool is in or out of cut [1,7].

D. Time domain simulation

Since the system is excited by cutting forces that can not be expressed by simple analytic functions, the equations can not be integrated in a closed form. Thus, the 4th order Runge-Kutta method is employed to solve the differential equation (1) [4,7]. A simulation system, which reads the input data of cutting conditions, machine tool characteristics, and other related parameters, and calculates the applied forces and outputs the vibration displacements of chatter in milling, has been developed.

E. Stability lobes

In order to analyze the stability of the system, the transfer function matrix, $\left[\left(\phi(i\omega) \right) \right]$, which gives the resulting displacements under the influence of the external forces, is considered. Since the x and y directions are considered to be orthogonal, the cross terms are zero, $\phi_{xy} = \phi_{yx} = 0$. With those assumptions the eigenvalues of the system are obtained and the stability lobes calculated [1,2,7]. Then the following eigenvalue equation is to be considered [1],

$$\det\left[[I] + \Lambda \cdot [\phi_o(i\omega_c)] \right] = 0 \qquad (5)$$

where $\phi_o(i\omega_c)$ is defined as the oriented transfer function matrix, which is obtained multiplying the milling force coefficients matrix and the transfer function matrix, as it is shown in [1]. The eigenvalue, Λ of the characteristic equation (5) is,

$$\Lambda = -\frac{n_t}{4\pi} \cdot b \cdot k_t \cdot \left(1 - e^{-i\omega_c T} \right) \qquad (6)$$

where ω_c represents chatter frequency, and T is the tooth period. The eigenvalue Λ, of the previous equation can be easily solved for a given chatter frequency ω_c static cutting factors, k_t, k_r, which can be stored as material dependent quantities for any milling cutter geometry, radial immersion, and transfer function of the tool and work-piece system. Then, the stability lobes are calculated plotting the expression of chatter-free axial depth of cut, $b_{\lim}$, versus spindle speed, N_s [1,2,7].

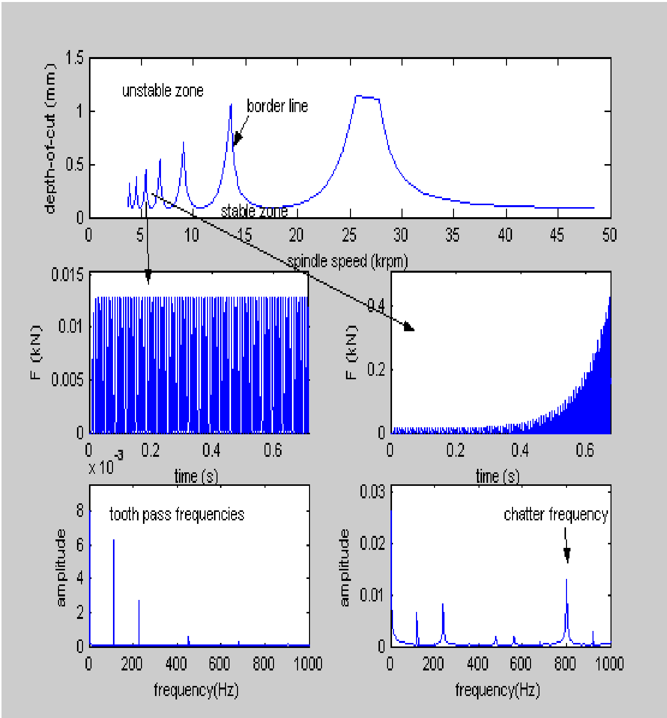

Figure 2. The chatter vibration representation in milling system, stability chars, force time response and force frequency response.

III. EXPERT SYSTEM

A. Milling process determination and preliminary rules

To carry out the tool selection and the determination of the values of the machining parameters, the milling process is determined. This paper is referred to two limitations. First, it is required the avoidance of the chatter vibrations. The productivity is given by a parameter known as metal removal rate (MRR). If the MRR is increased beyond a certain limit, self-excited vibrations are appreciated. This instability condition is characterized by a large level of vibration, poor surface finished and, usually, damage to machine tool components. The second limitation is given by the spindle power availability in the spindle motor. It delimits certain combinations of input variables, such as depth of cut, feed rate and spindle speed. This parameter bounds MRR as well. With those constrains, the “input space” can be obtained.

Due to uncertainties in the model, the lobes are constructed, not by replacing pure imaginary roots into the characteristic equation, but adding a positive real number to them. To have a robust system, it has been taken into account a confine in a programmed maximum depth of cut as well.

Then the following algorithmic methodologies are used, which are called **preliminary rules**:

- **Rule 1**: Stability margin to ensure that the system plays in a stable region due to uncertainties in the model.
  - **Rule 1.1**

  A small stability margin is selected for calculating the border line in the lobes char. For that reason it is added a positive real number into characteristic equation when the lobes are calculated, i.e, $i \cdot \omega \rightarrow i \cdot \omega + \delta, \delta > 0$. In this way, a stability threshold is considered against a possible bad modeling of the system.
  - **Rule 1.2**

  A margin at the final expression for chatter free axial depth of cut, which improves the robustness of the system, is taken into account. It can be expressed mathematically as, $b_{\lim} = \alpha \cdot b_{\lim}$, $0 < \alpha < 1$. This rule lets a better control capacity in the spindle speed parameter. On the other hand, the optimal MRR decreases.
- **Rule 2**: Search in the space parameter, spindle speeds, feed rates, and axial depth of cuts for the configurations satisfying constraints given by Rule 1.
  - **Rule 2.1**

  Calculate lobe chars and find the boundary points, (N_s, b) spindle speed – axial depth of cut pairs, between the stable and unstable zone.
  - **Rule 2.2**

  Calculate the admissible cutting parameter space, $Q := (N_s, b, s_t)$ in which the system is stable against chatter vibrations and the power consumption is less than the power availability in the spindle motor.

B. Tool selection

In this section, an approach for tool selection is suggested. It is based on a defined tool cost model. This function gives a criterion to distinguish the behavior of different cutters. Each one is characterized by the following properties: $T_i = (\omega_{xi}, \omega_{yi}, \xi_{xi}, \xi_{yi}, k_{xi}, k_{yi}, n_{ti}, D_i)$, where, $(\omega_{xi}, \omega_{yi}) \in \omega$, is the tool natural frequency, $(\xi_{xi}, \xi_{yi}) \in \xi$, is the tool damping ratio, $(k_{xi}, k_{yi}) \in k$, is the tool static stiffness, n_{ti} is the number of teeth, and D_i is the diameter for each tool, T_i, $i = 1, 2, .., N$, where N is the number of milling tools available to the designer. ω is the set of tools´ natural frequencies, conformed by the pairs (ω_x, ω_y) for each tool, ξ is the set of tools´ damping ratio, conformed by the pairs (ξ_x, ξ_y) for each tool and tool static stiffness set k is composed by (k_x, k_y) for each tool.

1) Tool cost model definition

The selection of a suitable tool is one of the final purposes of this paper. A tool cost function has been developed to carry out this intention. The constraints, which affect the cost model, are maximum MRR, minimum power consumption and maximum range against possible perturbations in tool rotational motion. Then, the tool cost model for a single milling process can be calculated using equation (7).

$$C(R,q,c_1,c_2) = c_1 \cdot k'_{1o} \cdot P_t + c_2 \cdot {k'_{2o}}/{MRR} + c_3 \cdot {k'_{3o}}/{\Delta N_s} \quad (7)$$

with $\sum_{i=1}^{3} c_i = 1$, $c_i \geq 0$, $q \in Q$, and $R \in T$,

$$P_t = P_t(R,q) = V \cdot \sum_{j=1}^{3} F_{tj}(\phi_j), \forall q \in Q \qquad (8)$$

T represents the set of available tools, Q is the admissible cutting parameter space, P_t is the cutting power draw from the spindle motor, n_t is the number of teeth, $V = \pi \cdot D \cdot N_S$, D is the diameter of tool, and N_S is the spindle speed. The MRR is defined as $MRR = a \cdot b \cdot s_t$, where a is the radial depth of cut, b is the axial depth of cut and s_t is the linear feed rate. ΔN_S is a security change in spindle speed to have an error margin because of a possible perturbation in this variable. The parameters, $k'_{1o} = {1}/{P_{t\max}}$, $k'_{2o} = MRR_{\max}$ and $k'_{3o} = \Delta N_{s\max}$, $P_{t\max}$ where is the maximum power available in the spindle motor, $MRR_{\max}$ is the maximum material remove rate avoiding chatter vibrations and spindle power limitations calculated between all tools proposed, and $\Delta N_{s\max}$ is the maximum measured value of this variable between the candidates cutters. Those parameters are included in (8) to have a tool cost model with the same magnitude terms and a relative parameter between all the candidates cutters involved.

C. Optimization rules

The above defined tool cost function is used to select the appropriate tool and cutting parameters, through the following optimization rules.

*1) **Rule 3** : Weight factors selection*

To select suitable values of c_i, their meaning has to be perceived. c_1, measures the importance of the spindle power consumption. If c_1 is near to one the minimum spindle power consumption is important to take the decision. If it is near to zero, the opposite effect, happen. The close values of c_2 to 1 demand machine productivity, and c_3 close to 1 improves the system stability against chatter.

The expert system ensures the spindle power consumption is smaller than the spindle power availability, through Rule 1. It takes into account stability problems against chatter, through Rule 2. Thus, the constants c_1 and c_3 give another additional margin in those variables. In this way, the value c_2 should be chosen longer than the others since it appears to have more importance in the behavior of the total system. Then, the c_1 can be selected, such that, $0 \leq c_1 < 0.1$, the c_3, $0 \leq c_3 < 0.2$ and $c_1 + c_2 + c_3 = 1$.

*2) **Rule 4** : Tool selection criterion*

A simple criterion for cutter selection has been developed. It reads the minimum values of the cost function for each tool, compare them, and select a tool corresponding with the cost minimum value.

The selection criterion is, mathematically, expressed as:

- Compute, $C(R_i, q_j, c_1, c_2)$; $\forall q_{ij} \in Q_j$ satisfying rule 2.2, and each $R_i \in T_i$, $i \in \overline{N}$, where $j \in \overline{N}_p = \{1,..,N_p\}$ is the space of the cutting parameter.
- Compute, $tool = \arg\left\{\min_{i \in \overline{N}, \forall Q_j}\left\{C(R_j, Q_j, c_1, c_2)\right\}\right\}$ obtaining the appropriate tool.

Following the rules, the expert system provides an appropriate cutter among the candidates.

*3) **Rule 5** : Cutting parameter selection*

Once the tool has been selected, it is required to take into account the output signal characteristics to obtain the cutting parameters. With this purpose, another two cost functions have been designed. The first studies the temporal behavior and the second the frequency response. These functions are added to the first one. The resultant cost function is used to obtain the optimal cutting parameters for the selected tool.

a) Temporal response cost model definition

The temporal response cost model is the maximum overshot (M_p) and the settling time (t_s) dependent function:

$$C_t(T_{tool}, Q_j, c_{1t}, c_{2t}) = c_{1t} \cdot {t_s}/{t_{s\max}} + c_{2t} \cdot {M_s}/{M_{s\max}} \quad (9)$$

where $t_{s\max}$ and $M_{s\max}$ are the maximum settling time and maximum overshot between the input space cutting parameters allowable, T_{tool} is the selecting tool according with the section III.B and $\sum_{i=1}^{2} c_{it} = 1$, $c_{it} \geq 0$.

b) Frequency response model definition

The frequency response cost model is depended on the relation between the first and second harmonics, R_{12h}, and the relation between the first harmonic frequency and the chatter frequency, R_{1ch}. That is:

$$C_f\left(T_{tool},Q_j,c_{1f},c_{2f}\right)=c_{1f}\cdot {R_{12h}}\big/{R_{12h\max}}+c_{2f}\cdot {R_{1ch}}\big/{R_{1ch\max}} \quad (10)$$

where $R_{12h\max}$ and $R_{1ch\max}$ are the maximums of those parameters between the input space cutting parameters allowable, T_{tool} is the selecting tool according with the section III.B and $\sum_{i=1}^{2}c_{if}=1$, $c_{if}\geq 0$.

c) Total cost function for cutting parameters selection

The total cost function is a lineal combination of C, C_t, and C_f, which is defined as:

$$\begin{aligned}&C_{\text{resultant}}(T_{tool},Q_j,c_{1r},c_{2r},c_{3r})=c_{1r}\cdot C(T_{tool},Q_j,c_1,c_2,c_3)+\\&+c_{2r}\cdot C_t(T_{tool},Q_j,c_{1t},c_{2t})+c_{3r}\cdot C_f(T_{tool},Q_j,c_{1f},c_{2f})\end{aligned} \quad (11)$$

where $\sum_{i=1}^{3}c_{ir}=1$, $c_{ir}\geq 0$, and T_{tool} is the selected tool.

d) Cutting parameters selection

A simple criterion for cutter selection has been developed. It reads the minimum values of the cost function for each tool, compare them, and select a tool corresponding with the cost minimum value.

The selection criterion is, mathematically, expressed as:

- Compute, $C_{\text{resultant}}\left(T_{tool},Q_j,c_{1r},c_{2r},c_{3r}\right);\forall q_{jtool}\in Q_{tool}$; satisfying rule 2.2.
- Compute, $Q^*=\min_{\forall Q_j}\left\{C\left(T_{tool},Q_j,c_{1r},c_{2r}\right)\right\}$ and obtain the optimal input cutting parameters for the selected tool.

Then, the expert system provides an appropriate tool between the candidates and its cutting parameters, such as, spindle speed, depth of cut and feed rate.

*4) **Rule 6**: Weight factors selection for temporal and frequency functions*

To select the values of c_{ir}, it has been taken into account that the most important term in C_{result} is C, it is because C_t and C_r are corrected terms. For this reason, it should be taken the c_{1r} about 0.8 and, c_{2r} and c_{3r}, about 0.1 each one.

IV. EXAMPLE

For the validation of this method, the above study has been applied for practical cutters and straight full-immersion up-milling operation. The example done for two tools with the following characteristics, according with the section II.C notation:

$T_1=\left(603,666,3.9,3.5,5.59,5.715,3,30\right)$;

$T_2=\left(900.03,911.65,1.39,1.38,0.879,0.971,2,12.7\right)$;

The natural frequency is measured in hertz, the tool damping is in %, the tool stiffness is in ${kN}/{mm}$ and the diameter of the tool is in mm. Other related parameters are the tangential cutting pressure which is measured in ${KN}/{mm^2}$, $k_{t1}=k_{t2}=600$ and the proportional radial cutting pressure constant $k_{r1}=0.3$ and $k_{r2}=0.07$, the cutting coefficients are assumed to be constant for a tool-work material pair. The stability margin factor is taken as $\delta=0.05$ and the stability margin factor for axial depth of cut is $\alpha=0.95$.

The analytical milling test was conducted using spindle speeds with increments of 1000 rpm, axial cutting depth, started with its minimum value in the stability border line divided by ten, and it is increased in steps of the same size. The selection of feed per tooth is from 0.05 to 0.55 mm, which are typical values in those operations, and can be delimited by the spindle power availability, which is $745.3W$.

The resultant tool is that leading to the minimum cost function, C. In figure 3, it is shown the values of tool cost function as $c1$ parameter varies. The c_3 has been taken as a constant $c_3=0.025$, and $c_3=1-c_1-c_3$. This study has been done to illustrate the influence of the ci parameters in the tool cost function. It is observed the tool T_1 has a better behavior respect to the tool T_2 for all value of c_1. In figure 4, the same study has been carried out for a different value of c_3, $c_3=0.075$, it is observed the same results.

Figure 5 shows a more general analysis, in which the minimum of the tool cost function for all possibilities of $c1$, c_2 and c_3, with the restriction $c_1+c_2+c_3=1$ is displayed.

This analysis has revealed that the first tool is better than the second one for all combinations of the c_i parameters. Thus, the output of the expert systems will be the first tool, while the cutting parameter can be obtained from the minimum of tool cost function for the selected tool for any values of c_1,c_2,c_3.

This method can be applied to any number of selected tools generating in a automatic task the best one to be used in the system.

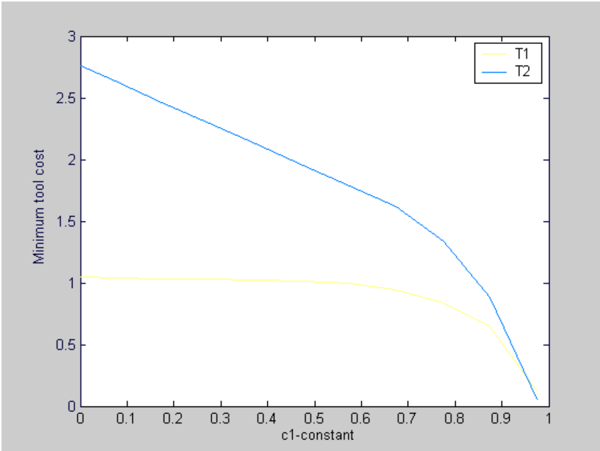

Figure 3. Minimum tool cost function versus c1 varies, c3=0.025.

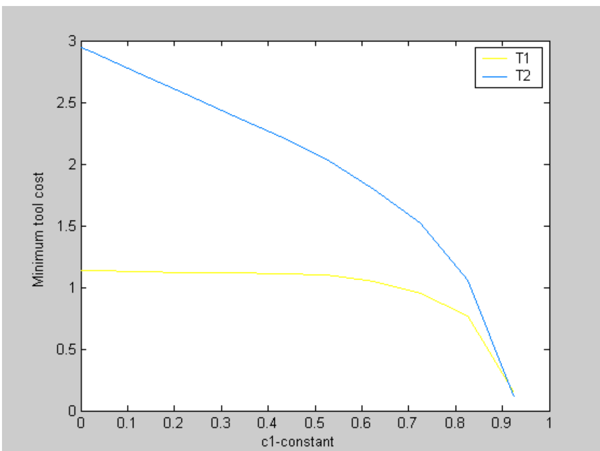

Figure 4. Minimum tool cost function versus c1 varies, c3=0.075.

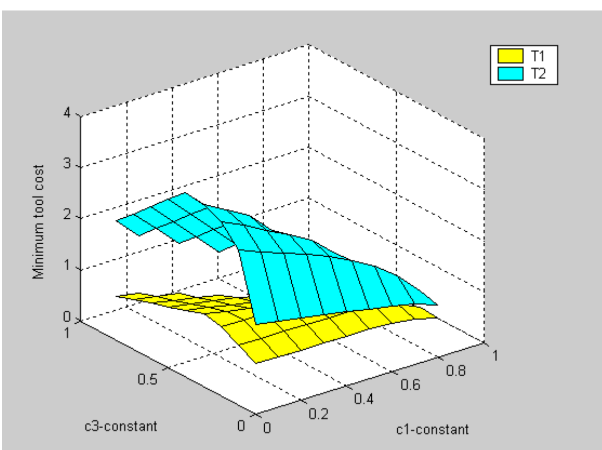

Figure 5. Minimum tool cost function versus c1,c2, c3 varies

The cutting parameters are obtained from section III.C, rules . For the example case, where $c_1 = 0.2, c_2 = 0.6, c_3 = 0.2$, $c_{1t} = c_{2t} = 0.5$, $c_{1f} = c_{2f} = 0.5$ and $c_{1r} = 0.8$, $c_{2r} = 0.1$, $c_{3r} = 0.1$ the obtained cutting parameters are the spindle speed equal to $1000rpm$, axial depth of cut equal to $1.4734mm$ and feed per tooth equal to $0.4944mm$.

V. Conclusions

An efficient approach for mill cutter 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 constraints of operations, such as, power availability and robust stability against chatter vibration. Furthermore, a tool cost model function, built from the expert system rules, is proposed to evaluate the possible performance of each candidate tool in milling process. This performance index is then used to select an appropriate tool. Adding the time and frequency designed cost functions, to the first one, a resultant cost function is obtained. It is used for the operation cutting parameters selection. A simulation example showing the behavior of the system is presented.

Acknowledgment

The Authors are very grateful to MCYT by its partial support through grant 2003-00164 and to the UPV/EHU through Project 9/UPV 00I06.I06-15263/2003.

References

[1] S. Y. Liang, R. L. Hecker and R. G. Landers, "Machining Process Monitoring and Control: The State of the Art", *Journal of Manufacturing Science and Engineering,* Vol.126, pp. 297-310, 2004.

[2] S. V. Wong and A. M. S. Hamouda, "The development of an online knowledge-based expert system for machinability data selection", *Knowledge-Based Systems,* Vol.16, pp. 215-219, 2003.

[3] M. C. Cakir, O. Irfan and K. Cavdar, "An expert system for die and mold making operations", *Robotics and Computer-Integrated Manufacturing,* Vol.21, pp. 175-183, 2005.

[4] A. Vidal, M. Alberti, J.Ciurana and M. Casadesús, "A decision support system for optimizing the selection of parameters when planning milling operations", *International Journal of Machine Tools and Manufacture,* Vol.45, pp. 201-210, 2005.

[5] I. D. Carpenter and P. G. Maropoulos, "A flexible tool selection decision support system for milling operations", *Journal of Materials Processing Technology,* Vol.107, pp. 143-152, 2000.

[6] Y. Altintas, *Manufacturing Automation*, Cambridge University Press, 2000

[7] L.Rubio and M. De la Sen, "Analytical procedure for chatter in milling", Southeastem Europe, USA, Japan and European Community Workshop on Reseach and Education in Control and Signal Processing, June 14-16, 2004, Cavtat, Croatia.