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Some aspects about Milling: Expert System for cutting parameters selection and Control Designs

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1. Introduction

Milling is a mechanical process which consist of the relative movement between feeding the work-piece and rotating the multitooth cutter, to remove material from the work-piece. Milling is used in industry for the manufacturing of mechanical components. During a operation static and dynamic effects can lead to undesared states, such as stick slip friction and forced and self-excited oscillations (Wiercigroch & Budak 2001). These oscillations, also called chatter oscillation, can culminate in non-smooth work-piece surface, inaccurate dimensions and excessive tool wear (Altintas 2000 , Landers 1997). The regenerative effect is the most widely recognized which causes chatter. Spindle speed selection or modulation and absorbers vibrations are the main solutions to supress chatter without reduce the productivity (Ganguli 2005). But, the difficulties to introduce these techniques and the increasing competence lead to use intelligent techniques to evaluate process parameters, such as, time requeriments, programmed cutting parameters, machine tool selection and/or cuting tools selection (Wong & Hamouda 2003).

The present document covers some aspects of the mentioned. First, an analytical guidance for description, detection and suppresion of chatter in milling system is given. Then, an expert system is proposed to select an adequate tool, among the available set, and cutting paramaters according to productivity, power compsumsion or availavility, and robustly stability against posible perturbations in the cutting parameters requeriments. The expert system suply an informatic tool to obtain cutting conditions independently of the machine operator, and it is also intended to be programmed by them. Once the cutting parameters has been selected, a control strategy is required. Thus, control of milling operations, and especially the adaptive control, has an extensive research in manufacture literature, since they reduce costs, save time and in general, protect the machine (Ralston & Ward 1988). Model reference adaptive control strategy is developed to program at Computer Numerically Controlled (CNC). A fractional order hold ($\beta - FROH$) is proposed to discretize the modelled continuous system of the milling machine. The extra degree of freedom, β, allow the programmer tuned this parameter to a better system response behavior, in comparison with a zero order hold typically used in literature.
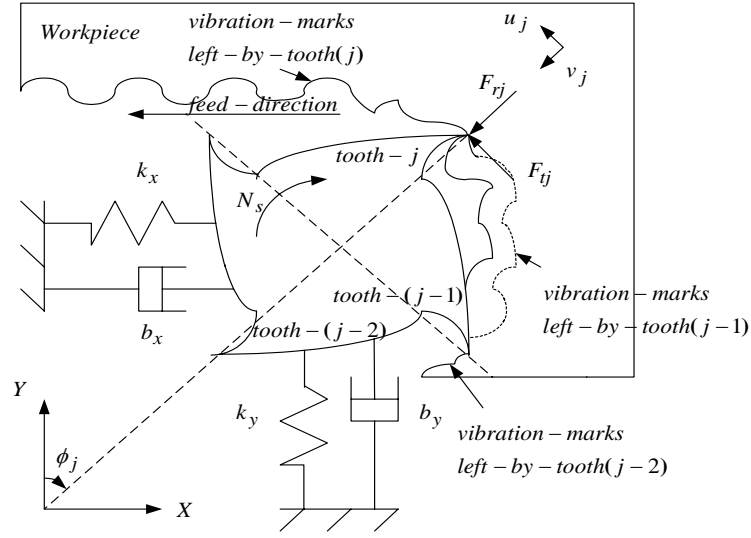
Figure 1 : End Part of the milling system

2. Milling system description

The dynamic milling system is modelled by the interaction between the tool and the work-piece. The milling cutter and the work-piece are usually represented by transfer functions with multiple degrees of freedom, which are obtained from the experimental modal analysis. The model developed here assumes the cutter to have two orthogonal degrees of freedom and the work-piece to be rigid (figure 1).

A. Dynamic model

Then, the dynamic model of the milling cutter has a mode of vibration in each direction, X and Y, while the feed direction of the work-piece is along the X-axis. The milling cutter has n_t teeth, which are equally spaced. Thus, the dynamics of the system is given by the differential equations (Li, H. and Li, X.):

$$m_x \cdot \ddot{x} + c_x \cdot \dot{x} + k_x \cdot x = \sum_{j=0}^{n_t - 1} F_{xj}(t) = F_x(t)$$

$$m_y \cdot \ddot{y} + c_y \cdot \dot{y} + k_y \cdot y = \sum_{j=0}^{n_t - 1} F_{yj}(t) = F_y(t)$$

(1)

where x and y are the dynamic displacements of the cutter structure into the X and Y axes, m_i, c_i and k_i are the mass, damping and stiffness of the tool, F_{xj} and

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F_{yj} are the projections into the two orthogonal axis of the cutting force, F, applied by the jth tooth on the work-piece.

B. Cutting force model

A simple model of the cutting forces will be discussed in this sub-section which expresses the tangential cutting force to be proportional with the instantaneous chip thickness.Despite this simplicity, this model captures the essence of the process. Hence,

$$F_t(t) = K_t \cdot b \cdot h(t) \tag{2}$$

where K_t is the specific cutting force parameter, b is the axial depth of cut measured perpendicular to the figure 1 plane, and $h(t)$ is the instantaneous chip thickness. In addition, the radial force may also be expressed in terms of the tangential force as,

$$F_r(t) = K_r \cdot F_t(t) \tag{3}$$

where K_r is a proportional constant. This cutting force model has been widely used by several authors, and was first proposed by Kroenigsberger, A. and Sabberwal, S.

C. Un-deformed cut chip thickness

The most critical variable in (2) is the chip thickness because it changes not only with the geometry of cutting tool and cutting parameters, but also with the uneven surface left by the previous passes of the cutting tool. Hence, after determining the chip thickness for an uncut fresh surface, this thickness must be compared with the undulations left by the cutting tool during subsequent passes at the same position to obtain the instantaneous thickness of the material left to be removed. This process is known as *regenerative chatter*. The total chip load consist of a static part, h_{st}, and dynamic components caused by the vibrations of the tool at present and previous tooth periods. This dynamic contribution to the chip-thickness can be modelled through a set of parameters usually known as inner v_j, and outer $v_{j,o}$, modulations :

$$h = \left(h_{st} + \left(v_{j,o} - v_j \right) \cdot g\left(\phi_j \right) \right) \tag{4}$$

h_{st} is attribuited to rigid body motion, determined from the feed per tooth s_t by:

$$h_{st} = s_t \cdot \sin \phi_j \tag{5}$$

The chip thickness is measured in the radial direction, with the coordinate transformation,

$$v_j = -x \cdot \sin \phi_j - y \cdot \cos \phi_j \tag{6}$$

being x and y the dynamic displacements of the cutter structure at the present period. The dynamic displacements of the cutter at previous tooth periods, v_j^o is usually modulated by the value of v_{j-1} of previuos tooth $(j-1)$.

Then, the regenereative chatter is modelled as (Altintas, Y. 2000),

$$h_j(t) = s_t \cdot \sin \phi_j(t) + \left[-x(t-T) \cdot \sin \phi_j(t) - y(t-T) \cdot \cos \phi_j(t) \right] - \\ - \left[-x(t) \cdot \sin \phi_j(t) - y(t) \cdot \cos \phi_j(t) \right] \tag{7}$$

where t is time and T is the tooth period.

D. Stability lobes

The chatter stability lobes make up a spindle speed dependent dividing line between stable and unstable axial depth of cut. It is obtained from the knowledge of the system dynamics. The border line between stable and unstable axial depth of cuts is related to the spindle speed as

$$b_{\lim} = -\frac{2\pi \Lambda_R}{n_t \cdot K_t} \left(1 + \kappa^2 \right) \tag{8}$$

where $\kappa = \dfrac{\Lambda_I}{\Lambda_R} = \dfrac{\sin \omega_c T}{1 - \cos \omega_c T}$, being Λ_R, Λ_I the real and imaginary parts of the eigen-value of the characteristic equation of the dynamic milling equation, n_t the number of teeth and K_t the specific tangential cutting pressure.

The relationship between the chatter frequency, ω_c and the tooth passing period, T, is given by

$$\omega_c T = \varepsilon + 2k\pi \tag{9}$$

being k the integer number of full vibration waves (i.e., lobes) imprinted on the cut arc and ε the phase shift between the inner and outer modulations (present and previous vibration marks). The spindle speed is calculated by finding the tooth pass period T,

$$N_s = \frac{60}{n_t \cdot T} \tag{10}$$

which gives the relationship between the spindle speed and the critical stable axial depth of cut which is commonly referred to as "stability lobes" (Altintas, Y.(2000) and Budak, E. & Altintas, Y.(1998)).

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E. Time domain simulations

The stability charts give broad information about a range of milling operation conditions, indicating the stable and unstable combinations of the axial depth of cut and the spindle speed. To improve the accuracy of the predictions and to gain more insight into the cutting operation, time domain simulation programs have been developed. Simulations are capable of producing information about severity of any resulting vibration, the surface left by the operation, the magnitude of the forces, the frequency of the vibration and so on. The time domain method provides a realistic simulation of the cutting process and chatter instability, since the number of assumptions involved is minimal. Thus, the 4th order Runge-Kutta method is employed to solve the differential equations (1) in the time domain (Smith & Tlusty 1993, Li & Li 2000).

F. Chatter detection and suppression

An algorithm for the monitorization the detection of chatter and a strategy for the suppression have been extensively researched in the field of the milling process in analytical and experimental ways, for instance see (Delio et. al. 1992, Landers 1997). In this section, it is intended to give an analytical method to chatter detection. On the other hand, the suppresion of chatter has been widely researched. The main ways are spindle speed selection, spindle speed modulations and vibration absorbers.

1) Chatter detection

The automatically chatter suppression leads firstly to necessity of an algorithm to detect the vibration. Analytically, Li et. al. 2003 proved the effectiveness of the criteria based on the predicted forces. The algorithm visualizes the relative displacements between the tool and the work-piece through a statistical value which measures the oscillations due to the regenerative effect. The non-dimensional coefficient, η, is defined as:

$$\eta = \frac{\max\left(\left\|F_{dy}\right\|\right)}{\max\left(\left|F_{st}\right|\right)} \tag{11}$$

where F_{dy} is the cutting force predicted using dynamic cutting force model where the regenerative effect of the equation (7) is taken into consideration, and F_{st} is the resulted cutting force using the static cutting force model and the cutting tool and the work-piece remain rigid. The threshold of instability is selected to be 1.3, then, $\eta \geq 1.3$ can be selected as instability criterion. Other similar parameter to detect chatter analytically is given in Campomanes & Altintas 2003.

2) Chatter suppression

Chatter affects the performance of milling machine, limits productivity of cutting processes, causes poor surface finish, reduces dimensional accuracy, increase the rate of tool wear and reduce the life of milling machine. *Conservative cutting conditions*, using the lobes charts, is the most extensive method used in manufacturing environments to avoid chatter. However, great efforts have been done to increase the productivity without losing efficiency.

a) Spindle speed selection

Other technique which uses the stability charts to suppress chatter is by adjusting the spindle speed to stay within two lobes. In this way, the milling system provides their maximum depth of cut for a given spindle speed increasing the system productivity. The selected lobes are depended on the machine tool requirements such as spindle power or spindle torque.

The main drawbacks are the systems with several coupled modes and the changes in the system parameters due to changes in the work-piece geometry upon cutting.

A more detailed explain can be found in Smith & Tlusty 1992.

b) Spindle speed modulation

Michels, V. et al. demonstrated enhancement of the stability in systems with time varying delay by modulating the point-wise delay, T, in equation (7). In the case of milling, modulation of spindle speed is roughly equivalent to modulation of the time delay between successive tooth inserts occupying the same angular position (Sastry et. al. 2001). Then, the spindle speed is varied about a nominal value, typically in a sinusoidal manner:

$$N_S = N_{SO}\left(1 + \alpha \cdot \sin\left(2\pi f_{SS} t\right)\right) \tag{12}$$

where N_{SO} is the nominal spindle speed, α is the amplitude ratio, f_{SS} is the signal frequency and t is the time. Although, there are some analytical approach (Jayaram et al. 2000, Sastry et al. 2001, Insperger et al. 2003, and references therein), even successfully experimental cases (Altintas & Chan 1992) to suppress chatter in this way, it has not been obtained a clear method to program the amplitude and frequency of the sinusoidal wave.

c) Vibration absorbers

The stability lobes give a pattern to know the effects of increasing or decreasing the machine tool structural parameters. Merrit 1965 was first showed that the minimum value of the limiting width of cut is directly proportional to the structural damping ratio in turning. In milling, as the structural damping ratio increases, the lobes shift

slightly to the left and the asymptotic stability boundary shifts up (Landers 2005), improving the stability.

Structural damping can be augmented either by passive or off-line and active or on-line means. Smart fluids such as electrorheological (Wang & Fei 1999) or magnetorheological (Segalman & Redmond 1996) fluids or active damping (Dohner et. al. 2004, Ganguli 2005) are examples to suppress chatter actively.

The above introduced methods enhance production and quality of process avoiding the undesired effects caused by the presence of chatter. Nevertheless, these methods suffer from a number of drawbacks which make their application limited or unprofitable. For example, the application of passive or active dampers in the machine requires the machine to be specifically designed. Furthermore, active dampers based on electro/magneto-rheological elements increase the final cost of the machine and causes additional maintenance work. On the other hand, spindle speed modulation leads to complex analytical systems implementation by usual operators hard in everyday work. In conclusion, the field of chatter suppression is still an open research field whose key point is the determination of an adequate set of cutting parameters avoiding chatter while being this set of parameters easy to find and formulate. In the following section, an expert-system based method is developed as a solution to this problem. The expert system provides adequate values for cutting parameters which not only the stability and absence of chatter in the system but also an improved machine behavior taking by into account an optimality criterion. Thus, expert system appears as a feasible method to deal with chatter suppression and efficiency of the milling process. Moreover, the expert system is able to select an adequate tool among a known available set.

3. Expert mill cutter and cutting parameters selection system

The main objective of the expert system is to obtain a mill cutter, among the available ones, which have an operating point or adequate cutting parameters, with maximum productivity (MRR), robustness stability against spindle speed perturbations and minimum power consumption. The developed expert system consists of the relative compliance between the tool and the work-piece, and it is predicted with analytical methods. Moreover, time and frequency domain milling process simulations have been developed, which are, then, used in the expert system definition. Then, the knowledge base is explained. Basically, it defines the allowable cutting parameters, which are known as cutting parameter space, for a given tool-work-piece configuration. It is based on the chatter vibrations avoidance, which limits the productivity of the process, and on a spindle power limitation criterion.

On the other hand, a novel tool cost function is designed to select the operating point. It depends on spindle power consumption, material removing rate (MRR) and on a stability criterion against possible perturbation in the spindle speed variable. Each term of the cost function has a proportional factor to have terms of approximately similar magnitudes. A weight factor which measures the importance of each term is also incorporated.

The proposed cost function is a measure of how the milling process is being carried out at certain operation condittions. The larger the cost function is, the worst operation conditions are. Thus, the cutter and cutting conditions which minimise the designed cost function are selected.

Then, the expert system takes tool characteristics, related tool-work-piece material parameters and milling operation as inputs and outputs the selected tool among the candidates and robust programmed cutting parameters.

A. Milling process determination and preliminary rules

In order to evaluate the system performance, a suitable tool and performance indices are needed. Milling processes, basically, consists of two phases roughing and finishing the surface. The main difference between these operations is to decide the most appropriate performance index for a given tool. The quality and geometric profile of the cutting surface is of paramount importance in milling finishing operation, whereas roughing -milling consists on removing a large amount of material from a blank.

This chapter deals with roughing milling operation. The rate at which the material is removed is called material removing rate (MRR). This parameter measures the productivity of machining processes. In milling operations, MRR is defined as the multiplication between axial and radial depth of cut, spindle speed, and feed. MRR upper limit is given by chatter vibrations and power deliver by the spindle motor. For certain combinations of cutting parameters, such as spindle speed, axial depth of cut and feed, either chatter vibrations are sensed, or the power available by the spindle motor is insufficient. Then, these parameters bound the roughing-milling operation productivity.

For those reasons, the input cutting parameter space is given by the cutting parameters as a first approximation, below the line at the stable stability lobes char while the power consumption is less than the power available by the spindle motor.

But, 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. Furthermore, to have a robust system, it has been taken into account a confine in a programmed maximum depth of cut.

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

Rule1: Stability margin setting to ensure that the system plays in a stable region, despite the system model uncertainties.

Rule 1.1: For calculating secure stability lobes char, a small stability margin is selected, i.e, it is supposed that the chatter vibrations happen at $\delta + i \cdot \omega_c$ instead of at $i \cdot \omega_c$. The reason is that the stability border line is calculated from a linear approximation. Then, $i \cdot \omega_c$ is replaced by $\delta + i \cdot \omega_c, \delta > 0$, when the stability border line is calculated. This rule is applied to the equation (13).

Rule 1.2: For improving the robustness of the system, a margin at the final expression for chatter free axial depth of cut has been taken into account, equation (18), i.e, $b_{\lim} = \alpha \cdot b_{\lim}, 0 < \alpha < 1$. This rule lets a better control capacity in the spindle speed. On the other hand, a better MRR selection is lost because of the above design simplifying process.

Rule2: For searching the allowable input space parameter, the set of spindle speed, Ns, axial depth of cut, b and feed rate, s_t the following rules are applied.

Rule2.1: Calculate the boundary points, spindle speed and axial depth of cut pairs, which compose the line between stable and unstable zones, satisfying Rule 1. This rule is obtained by plotting the stability lobes char, which gives the line between stable and unstable zones

Rule2.2: Calculate the admissible input space, $Q := (N_s, b, s_t)$. The boundaries spindle speed and axial depth of cut, gives the maximum spindle speed and axial depth of cut pairs without chatter vibrations (rule 2.1). The time domain simulation is used to obtain the applied force by the milling machine. As it will be then seen in the next section, the spindle power is force-dependent, which is spindle speed, axial depth of cut and feed rate dependent. Then, for a given spindle motor power available, the admissible input *cutting parameter space* is obtained.

A. Tool selection

In this section, an approach for tool selection is suggested. For this purpose, a tool cost model function is designed. The designed tool cost model is used to select the appropriate tool between the candidates though the optimization Rules, explained below.

Then, the study requires a given set of candidates milling cutters. Each one is characterized by the following properties:

$R_i = \left(\omega_{nxi}, \omega_{nyi}, \xi_{xi}, \xi_{yi}, k_{xi}, k_{yi}, n_{ti}, D_i, \beta_i \right)$ where $\left(\omega_{xi}, \omega_{yi} \right) \in W$ is the tool natural frequency, $\left(\xi_{xi}, \xi_{yi} \right) \in \xi$ is the tool damping ratio, $\left(k_{xi}, k_{yi} \right) \in K$ is the tool static stiffness, n_{ti} is the tool number of teeth, D_i is the tool diameter and β_i is the tool helix angle. $R_i \in T$, $i = 1, 2, .., N$, where N is the number of tools and T is the set of tools available to the designer. W is the set of tools' natural frequencies,

conformed by the pairs $\left(\omega_{nx}, \omega_{ny}\right)$ for each tool, ξ is the set of tools' damping ratio, conformed by the pairs $\left(\xi_x, \xi_y\right)$ for each tool and tools' static stiffness is conformed by $\left(k_x, k_y\right)$ for each tool.

B. Tool cost model definition

To carry out the selection of a suitable tool, a novel tool cost function has been conceived. The tool cost model for a single milling process can be calculated using the equation (20).

$$C\left(P_t, MRR, \Delta N_s; R, c_1, c_2\right) = c_1 \cdot NF_1 \cdot P_t + c_2 \cdot {NF_2}\big/{MRR} + c_3 \cdot {NF_3}\big/{\Delta N_s} \qquad (13)$$

with $\sum\limits_{i=1}^{3} c_i = 1$, $R \in T$, where $P_t = V \cdot \sum\limits_{j=1}^{n_t} f_{tj}\left(\phi_j\right)$,

$MRR = a \cdot b \cdot s_t \cdot N_s \cdot n_t$, ΔN_s takes its definition given below, and $q \equiv \left(N_s, b, s_t\right) \in Q$. Standardizing factors, NF_i, are defined as follow, $NF_1 = P_{tAv}^{-1}$, where P_{tAv} is the power available in the spindle motor, $NF_2 = MRR_{\max}$, where $MRR_{\max}$ is the maximum MRR with the chatter vibrations and spindle power restrictions calculated among all the candidate cutters and $NF_3 = \Delta N_{s,\max}$ where $\Delta N_{s,\max}$ is the maximum measured value of this variable among the candidate cutters.

The tool cost function is designed to minimize a tradeoff among MRR, power consumption, and a range against possible perturbations in tool rotational motion, dependent and inversely proportional to MRR and a range against possible perturbations and directly to power consumption. The designer keeps the capability of designing the weight of each of those terms according to design requeriments. He also keeps the capability of on-line adjusting such weights. A condition to be fulfilled is the scheme´s stability. For that purpose, all admisible operation points have to belong to the stability region delimited by the lobes which is corrected in the context of a worst case situation, so as to deal with possible uncertain locations of the operation points due to uncertainties in the model like for instance, unmodelled nonlinearities, neglected high-order harmonics and external disturbances.

These parameters have the following definitions:

Material or Metal -Removing Rate $\left(MRR\right)$

$MRR = a \cdot b \cdot s_t \cdot n_t \cdot N_s$, being a the radial depth of cut, b the axial depth of cut, n_t the number of teeth, N_s the spindle speed and s_t the linear feed rate. The MRR is a

parameter, which compares, the efficiency of the milling process. A larger *MRR* improves the process productivity.

<u>Cutting power draw from the spindle motor (P_t)</u>

The cutting power, P_t, drawn from the spindle motor is found from,

$$P_t = V \cdot \sum_{j=1}^{n_t} F_{tj}(\phi_j)$$

(14)

being $V = \pi \cdot D \cdot N_s$ the cutting speed and N_s the spindle speed. The tangential cutting force is given by:

$$F_{tj}(\phi_j) = K_t \cdot b \cdot h(\phi_j)$$

(15)

where b is the axial depth of cut, K_t is the cutting force coefficient, which are material dependent and is evaluated from experiments, and $h(\phi_j)$ is the chip thickness variation, which is feed rate s_t (mm/rev-tooth) dependent.

<u>Spindle speed security change (ΔN_s)</u>

An additional term, spindle speed security change, is added to the cost function model to be sure that chatter vibrations are avoided. The spindle speed security change, ΔN_s, measure the nearest spindle speed at which chatter vibrations happen to the supposed spindle speed it will be operated. This fact allows having an error margin due to possible perturbations in this variable.

To calculate analytically, ΔN_s, the following algorithmic methodologies are carried out. They are divided in two cases:

<u>Case I</u>: $k = 0$, this case corresponds to pairs, spindle speed-axial depth of cut, situated below the first lobe of the stability chars. Then, there is no lobe in the right part of the point. Suppose that (N_{sI}, b_I) is the point which ΔN_s has to be calculated:

a) If $b_{\min,cri} > b$, $\Delta N_s = abs(N_{s,\min,cri} - N_{s,I})$.

b) If $b_{\min,cri} < b$, $\Delta N_s = abs(N_{s,cri}(b_I) - N_{sI})$.

$b_{\min,cri}$ is the minimum value of the axial depth of cut corresponding to the border line, $N_{s,\min,cri}$ is its corresponding spindle speed, $N_{s,cri}(b_I)$ is the left-projection of the point (N_{sI}, b_I) into the nearest lobe.

<u>Case II</u>: $k \neq 0$, the point ,which ΔN_s has to be calculated, is situated between two consecutive numbered lobes in the stable region. Suppose that (N_{sII}, b_{II}) is the mentioned point, then $\exists k$ such that $N_{s,\min,cri}(k) < N_{sII} < N_{s,\min,cri}(k+1)$, where k is the lobe number, $k = 0,1,...S-1$, and S is the number of printed lobes , and

$N_{s,\min,cri}(k)$ is the spindle speed corresponding to the axial depth of cut minimum value on the border line, $b_{\min,cri}(k)$, for the k-lobe. Then:

a) If $b_{\min,cri}(k) > b < b_{\min,cri}(k+1)$

$$\Delta N_s = \min\big(abs(N_{s,\min,cri}(k) - N_s), abs(N_{s,\min,cri}(k+1) - N_s)\big)$$

b) If $b_{\min,cri}(k) < b > b_{\min,cri}(k+1)$

$$\Delta N_s = \min\big(abs(N_{s,cri}(k) - N_s), abs(N_{s,cri}(k+1) - N_s)\big)$$

where $N_{s,cri}(k)$ is the left-projection of the point (N_{sII}, b_{II}) into the k-lobe, and $N_{s,cri}(k+1)$ is the right-projection into the k+1-lobe. The case under consideration is graphically represented in figure 2.
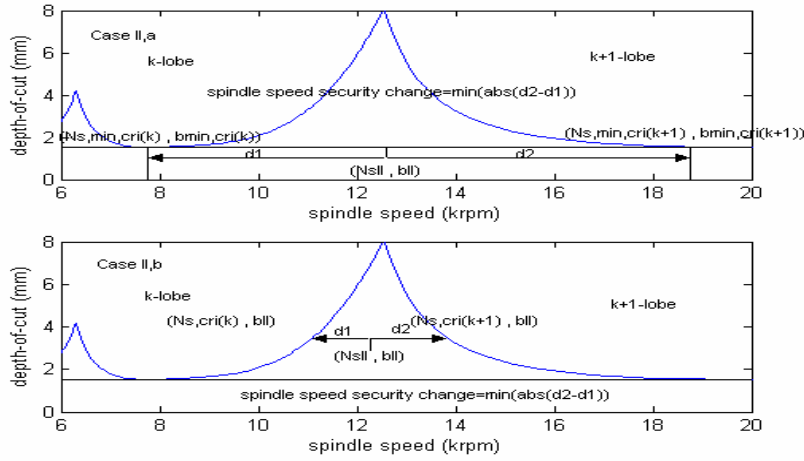

Fig. 2: Spindle speed security change, (ΔN_s), general case.

Furthermore, the other possible cases in the ΔN_s calculation are not considered, since they are unstable states cases. On the other hand, the calculated ΔN_s have been done taking into account Rules 1.1 and 1.2. Standardization factors, NF_i, are also added to the cost function to have terms with the same magnitude. Moreover, they make to have a relative term among all the candidates cutters involved. On the other hand, these terms ensure that the cost function will be comparable among the different cutters.

The values are the weights of the cost function terms. They $c_i, i = 1,2,3$ measure the importance of the cost function terms. The below optimization Rule 3 give a pattern to program the parameters c_i.

C. Optimization rules

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

Rule 3: Weight factors selection

The weight factors are intended to be programmed by the machine operator. An extended explanation of their meaning and their adequate selection is given in this section To select suitable values of c_i, $i = 1,..,3$, their meaning has to be perceived. The c_1-value measures the importance of the spindle speed consumption. A larger c_1 parameter is the more important to the spindle power consumption in the cost model function. The c_2 measures the machine productivity if the c_2 is near to one high productivity is required and if it is near to zero the productivity has no importance. The same reasoning is applied to the c_3, which measures the stability against possible perturbations in the spindle speed variable.

It has to be taken into account that the expert system, ensures that the spindle power consumption is always going to be smaller than the power available in the spindle motor, through Rule 1. Also, that the cutting parameter space has no sensed chatter vibrations through Rule 2.

Then, a possible criterion leading to a process with acceptable productivity, which is the main objective of the milling processes, c_2 about 0.75, and the other two constants will add 0.25, suitable values are $c_1 = 0.1$ and $c_2 = 0.15$.

Rule 4: Tool selection criterion

A simple tool selection criterion for cutter selection has been developed. For a given values of c_1, c_2, c_3, and a given tool characteristics, the cost function value is obtained for all the admissible input cutting parameter space. The minimum value of the cost function is stored. The procedure is repeated for all the available cutters. Comparing the minimum value of the cost function 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,

$$C\left(P_{tj}\left(q_j\right), MRR_j\left(q_j\right), \Delta N_{sj}\left(q_j\right), R_i, c_1, c_2\right) \tag{16}$$

for each $R_i \in T$, $i \in \bar{N}$, and $\bar{N}$ is the set of candidate tools and $\forall q_j \equiv \left(N_{sj}, b_j, s_{tj}\right)$ where $j \in \bar{N}_p = \left\{1,.., N_p\right\}$ is a discrete sub-space of the cutting parameters space where the cost function (20) is calculated.

For obtaining the selected tool, ST, compute

$$ST = \arg \min_{i \in \overline{N}} \left\{ C\left(P_t\left(q_j\right), MRR\left(q_j\right), \Delta N_s\left(q_j\right), R_i, c_1, c_2\right)\right\} \tag{17}$$

with $ST \in T$, obtaining the appropriate tool according to the criterion.

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

Note that the objectives of the expert system are to obtain a tool which has an operating point or adequate cutting parameters where the MRR will be higher than the others available tools, with a prescribed stability robustness and without consumption more power than the available in the spindle motor. Hence, the tool cost model is designed so as to minimize it. Furthermore, the power consumption will be minimum, and the MRR and stability robustness will be maximum, for a given values of c_1, c_2, and c_3. The $c_i, i = 1,2,3$, are designed by the machine operator.

Rule 5: Cutting parameter selection

To obtain the cutting parameters a simple criterion, which consist of calculate the cutting parameters which corresponds to the minimum value of the cost function above defined for a certain values of c_1, c_2, c_3. But, here, a new approach thought an auxiliary cost function is going to be applied. In this case, once the tool has been selected, another novel and complete cost function is designed in order to obtain the best cutting parameters. It is composed by the above defined cost functions and other two, which are time and frequency domain responses related. Then, the first new cost function studies the temporal behavior of the input cutting parameters, and the second one its frequency response. The resultant cost function is used to obtain the cutting parameters for the selected tool.

- Temporal response cost model definition

The temporal response cost model is defined as the maximum overshot $\left(M_p\right)$ and the settling time $\left(t_s\right)$ dependent function. Those characteristics are typical in the study of the time domain response of a system.

$$C_t\left(T_{tool}, Q_j, c_{1t}, c_{2t}\right) = c_{1t} \cdot \frac{t_s}{t_{s,\max}} + c_{2t} \cdot \frac{M_s}{M_{s,\max}} \tag{18}$$

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

- Frequency response cost model definition

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

$$C_f\left(T_{tool}, Q_j, c_{1f}, c_{2f}\right) = c_{1f} \cdot \frac{R_{12h}}{R_{12h\,\max}} + c_{2f} \cdot \frac{R_{12h}}{R_{1ch\,\max}} \qquad (19)$$

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

- Total cost- function model

The total cost function is, then, composed by the defined above three cost functions, the tool cost model, the temporal response cost model and the frequency response cost model.

For this case, the cutting parameters are calculated following the algorithm:

$$C_{resul\tan t}\left(T_{tool}, Q_j, c_{1r}, c_{2r}, c_{3r}\right) = c_{1r} \cdot C\left(T_{tool}, Q_j, c_1, c_2, c_3\right) + \qquad (20)$$
$$+ c_{2r} \cdot C_t\left(T_{tool}, Q_j, c_{1t}, c_{2t}\right) + c_{3r} \cdot C_f\left(T_{tool}, Q_j, c_{1f}, c_{2f}\right)$$

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

Compute, $C_{resul\tan t}\left(T_{tool}, Q_j, c_{1t}, c_{2t}, c_{3t}\right), \forall q_{jtool} \in Q_{tool}$, satisfying the rule 2.2.

Compute, $q^{**} = \arg\left\{\min_{\forall q_j}(C_{resul\tan t}(T_{tool}, q_j, c_{1r}, c_{2r}, c_{3r}))\right\}$ and obtain the input

cutting parameters for the selected tool.

Rule6:Process malfunctions: tunning c_1, c_2, c_3 values

Nevertheless, in programming the selected tool and cutting parameters, malfunctions of the process may lead to a poor behavior of the process. The most important are tool wear and burr formation (Landers et. al. 2002). These phenomena, which are common in the manufcturing processes, make that the analytical and experimental testes are not always in concordance. If it is happened, the follow algorithmic methodology could be aplied:

While $A_{chatter} > A_{toothpass}$, $c_2 \leftarrow 0.99 \cdot c_2$, $c_3 \leftarrow 0.01 \cdot c_1 + c_3$, end

where $A_{chatter}$ is the chatter frequency vibration amplitude, and $A_{toothpass}$ is the highest amplitude among the tooth passing frequency and its harmonics. So, a more stable state is obtained.

Rule7: Resultant cost function weight factors selection.

 To select the values of c_{ir} it has been taken into account the fact that the most important term in $C_{resul\tan t}$ is C by practical reasons. 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. The time and frequency domains weighting factors, $c_{1t}, c_{2t}, c_{1f}, c_{2f}$ are assumed to have the same value or be very similar.

Finally, figure 5 shows a scheme of the expert system. The developed expert system takes the α and δ constants, the tools´ modal parameters such as its natural frequency, damping ratio, tool static stiffness, the number of teeth, the radius of the tool, the helix angle, and the cutting constants for the work material and cutter (tools´ characteristics), the spindle power available and the cost function weight factors, as inputs and outputs the appropriate tool among the candidates and robust programmed cutting parameters.
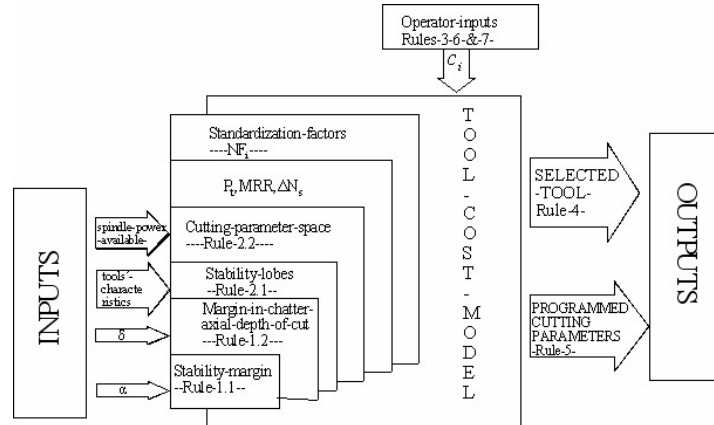

Fig. 3: Schematic expert system representation.

D. *Example*

For the validation of this method, the above study has been applied for two practical straight cutters and a full-immersion up-milling operation. The example considers the tools to have the following characteristics, according with the section III.B notation,

$R_1 = \left(603, 666, 3.9, 3.5, 5.59, 5.715, 3, 30, 0\right)$, and

$R_2 = \left(900.03, 911.65, 1.39, 1.38, 0.879, 0.971, 2, 12.7, 0\right)$.

 The natural frequency is measured in hertz, the tool damping is in %, the tool stiffness is in $KN \cdot mm^{-1}$ and the diameter of the tool is in mm. The work-piece is

a rigid aluminum block whose specific cutting energy is chosen to be $K_{1,2} = 600KN \cdot mm^{-2}$ and the proportionally factor is taken to be $k_{r1} = 0.3$, for the tool one, and $k_{r2} = 0.07$ for the other one. Other design expert system parameters are, the stability margin factor, $\delta = 0.05$ and the stability margin factor for the axial depth of cut, $\alpha = 0.95$.

The analytical test for mill cutter selection was conducted using spindle speeds with increments of $1000rpm$, axial cutting depth started with its minimum value in the stability border line divided by ten, and it is increased in steps of this same size, for a given spindle speed. The operation constraint on the maximum feed per tooth is 0.55 mm and the step integration is selected to be 0.05. The spindle power availability is $745.3W$.

The resultant tool is that leading to the minimum tool cost function value.

In figure 4, it is shown the values of tool cost function as c_1-parameter varies, the c_3-value has been taken as a constant $c_3 = 0.075$ and the c_2 follow the rule $c_2 = 1 - c_1 - c_3$.
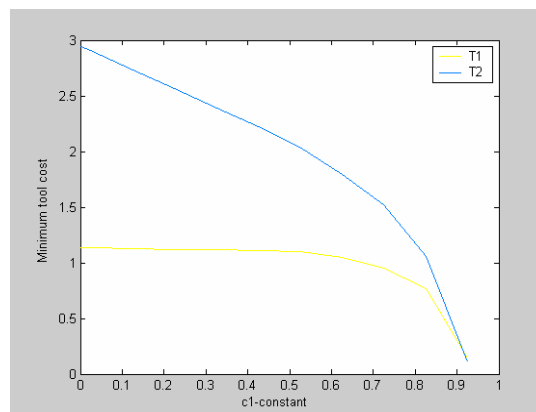

Fig. 4: Minimum tool cost function vs. c_1 varies, with $c_3 = 0.075$.

This study has been performed to illustrate the influence of the c_i parameters in the tool cost function. It is observed the tool R_1 has a better behavior respect to the tool R_2 for all possible value of c_1 and c_2, with $c_3 = 0.075$. Analyses with other values of c_1, c_2 and c_3 have been carried out and the results are similar, and the tool R_1 has a better behavior.

Then, a more general analysis shows in figure 5, in which the minimum value of the tool cost function for all possible combinations of c_1, c_2, c_3, with the restriction $c_1 + c_2 + c_3 = 1$ is displayed.

The analysis has revealed that the first tool has a better behavior than the second one for all combinations of the c_i parameters. Thus the output of the expert system is the first tool.
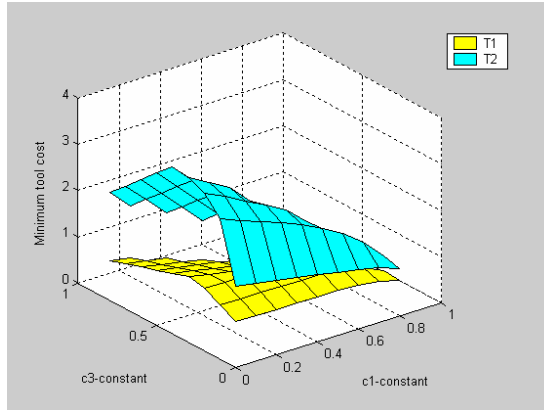
Fig. 5: Minimum tool cost function versus c_1, c_2, c_3 varies

For the cutting parameters selection, two steps have been done. First, the cutting parameter corresponding to the minimum of the tool cost function for the selected tool for values of $c_1 = 0.2, c_2 = 0.725, c_3 = 0.075$ is obtained. These values are $q^* = (5800, 0.4924, 0.2722)$.

It can be a well-done first approximation. For a more appropriate solution, taking into account the time and frequency domain system responses, the total cost function, $c_{resul\,tan\,t}$ has been calculated for the allowable cutting space parameter. The minimum value is saved for $c_{1t} = c_{2t} = 0.5, c_{1f} = c_{2f} = 0.5$, and $c_{1r} = 0.8$, $c_{2r} = 0.1$, $c_{3r} = 0.1$ the resulted programmed cutting parameters are $q^{**} = (5680, 0.457, 0.265)$.
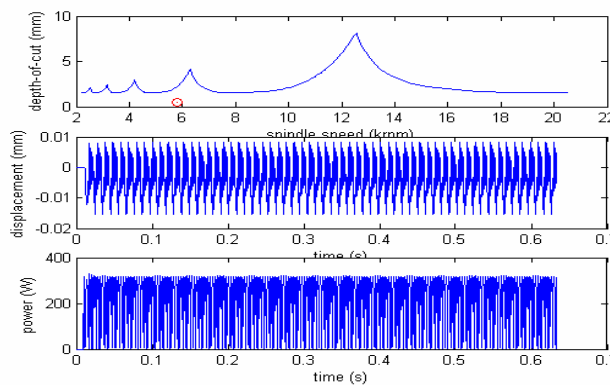

Fig. 6: Situation of the point q** in the stability diagram and tool displacement and power consumption time domain responses for the selected tool.

Figure 6 shows the situation for the stability lobes of the programmed point q^{**}, the tool displacement and the power consumption. It is observed that the point is

robustly stable and the power consumption is less than the power availability in the spindle motor, while the MRR measure becomes acceptable.

This method can also be applied to any number of selected tools generating in automatic task the best one to be used in the system. Moreover, the method can be used to schedule the relative compliance between the available tools and the used work-pieces materials. On the other hand, the expert system can be used to optimize the manufacturing process, in the sense of planning the adequate sequence of work-pieces to be manufactured for each tool in order to minimize the changes of tools. Finally, apart from being a cheep method, the expert system could be easily used by an inexpert human operator.

According to the established criterion the expert system, once the cutting tool has been selected, provides an operating point in a robust region of the lobes charts, for a given tool, optimizing time and frequency domains reponses and taking into considerartions process malfunctions, such as tool wear and burr formation. On the other hand, it is needed a control strategy to mantain the cutting force below a limit value to prevent fracture of the shank.

4. Milling forces adaptive control under $\beta - FROH$ discretization

The main objective of control in roughing milling operations is to maintain the cutting force at the desired level, manipulating the feed rate during milling in spite of variation of machining conditions, such as depth of cuts and spindle speed, and then dependent machining parameters, such as time average constants or/and material dependent values. Due to their variations the ideas from adaptive control theory has been widely used. It makes that the term adaptive control of machine tools is applied to systems that range from the simple to the very complex (Koren 1983, Koren 1997, Ulsoy & Koren 1989, Elbestawi et. al. 1990).

In the present section, the adaptive control theory has been applied to prove his efficiency when the milling system changes due to a sudden increase in the cutter immersion, as bench mark, to follow the reference cutting force (Tomizuka 1983, Altintas 2000, Peng 2004).

A.   System description

i. Continuous model

Milling systems are composed by a Computer Numerically Controlled (CNC), feed drive, motors, amplifiers and cutting process. A feed command f_c is sent to the CNC unit. The CNC unit sends voltage to the feed drive motors, which move the table at an actual feed velocity of f_a. Even though the machine tool drive servos are typically modelled as a high order transfer functions, they can be approximated as a second order transfer function at the range of the worked frequency (Altintas

1992). Besides, they can be tuned to be over-damped without overshoot, so that they can be approximated to have first order dynamics (Altintas 2000):

$$G_s(s) = \frac{f_a(s)}{f_c(s)} = \frac{1}{\tau_s s + 1} \tag{21}$$

where f_a and f_c are the actual output and command input values of the feed speed in (mm/s) and τ_s is a time constant, which is an average value dependent on the system dynamics, in this study, it is assumed to be 0.1 ms.

The chatter vibration free and resonant free cutting process, which results from equation (1), can be approximated as a first order continuous system (Altintas 2000) :

$$G_p(s) = \frac{F_p(s)}{f_a(s)} = \frac{K_c ba(\phi_{st}, \phi_{ex}, N)}{N_s \cdot n_t} \frac{1}{\tau_c s + 1} \tag{22}$$

where $K_c \left(N/mm^2 \right)$ is the cutting pressure constant, $b\,(mm)$ is the axial depth of cut, and $a(\phi_{st}, \phi_{ex}, N)$ is the immersion function, which is adimensional and may change between 0 and a proportinal value of the number of teeth, depending on immersion angle and the number of teeth in cut.

The combined transfer function of the system is composed by the feed drive servo and cutting system cascade dynamics,

$$G_c(s) = \frac{F_p(s)}{f_c(s)} = \frac{B_c(s)}{A_c(s)} = \frac{1}{(\tau_m s + 1)} \frac{K_c ba}{N_s n_t (\tau_c s + 1)} = \frac{K_p}{(\tau_m s + 1)(\tau_c s + 1)} \tag{23}$$

where the process gain is $K_p\,(N \cdot s/mm) = K_c ab/N_t n_s$.

The complete system is piecewise constant: admitting sudden changes in the cutting parameters remaining invariant between these changes.

To test the efficiency of the parameter adaptive controller proposes below, it is supposed that the tool have to mill a work-piece with the following geometry (figure 7). An axial depth of cut of 2 mm for a distance of 5.87mm, then 3 mm for 5.87 mm, 5 mm for 5.87 mm, too, and 3 mm for 7.55 mm, as it can be seen in figure 7, respectively in the feed direction with a constant spindle speed of 715 rpm; the work-piece is made of Aluminum 6067 whose specific cutting pressure is assumed to be $K_c = 1200 \frac{N}{mm^2}$. It is supposed that the only parameter which varies in the transfer function, equation (23), is the axial depth of cut, while the immersion funtion, the spindle speed, the time constants and the specific cutting pressures remain constants. A 4-fluted carbide end mill tool and full-immersed operation is taken into consideration.
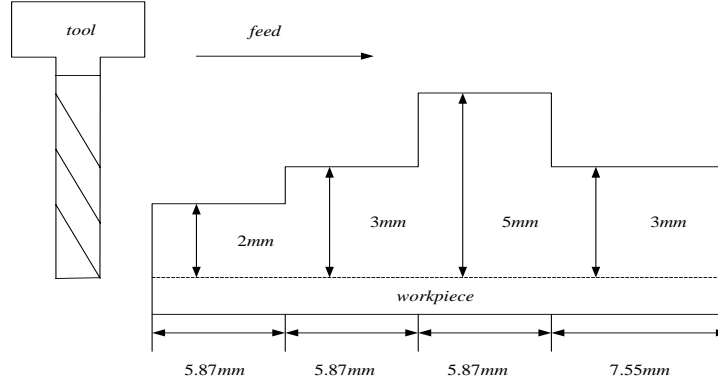
Figure 7: Milled path.

ii. *Discrete model under $\beta - FROH$*

A computerized strategy control requires a discrete model. Typically, a zero order hold is used in the manufacturing literature. Here, a fractional order hold of correcting gain $\beta \in [-1,1]$ is used to obtain the discrete transfer function of the continuous system explained above. It provides an extra degree of freedom, β, the gain of the fractional order hold. This extra degree of freedom can used with a broad variety of objectives such as to improve the transient response behavior, to avoid the existence of oscillations in the continuous time output of the system or to improve the stability properties of the zeros of the discretized system. In this way, this work is especially focused on the used of this kind of techniques to improve the transient response of the adaptive system by selecting an adequate value of the fractional order hold. Then, the discrete transfer function is calculated as follow (Bilbao-Guillerna et. al. 2005),

$$H_\beta(z) = Z[h_\beta(s) \cdot G_c(s)] \tag{24}$$

where $h_\beta(s) = \left(1 - \beta e^{-sT} + \dfrac{\beta\left(1 - e^{-sT}\right)}{Ts}\right)\dfrac{1 - e^{-sT}}{s}$ is the transfer function of a

$\beta - FROH$, where z is the argument of the $Z - transform$, being formally equivalent to the one step ahead operators, q, used in time domain representation of difference equations. This allows us to keep a simple unambiguous notation for the whole section content. The sampling time has been chosen to be the spindle speed, T, as it is usual for this kind of systems (Altintas 2000). Note that, when $\beta = 1$, the $FROH$ hold becomes a first order hold (FOH) and if $\beta = 0$ the zero order hold (ZOH) is obtained, as particular cases of $\beta \in [-1,1]$.

$$H_\beta(z) = \frac{B_\beta(z)}{z^{\delta_\beta} \cdot A(z)} = \frac{z-\beta}{z} Z[h_o(s)G_c(s)] + \frac{\beta(z-1)}{Tz} Z\left[h_o(s)\frac{G_c(s)}{s}\right] =$$

$$= \frac{B_\beta(z)}{z^{\delta_\beta} \cdot \left(z - e^{T/\tau_m}\right) \cdot \left(z - e^{T/\tau_c}\right)} \tag{25}$$

Furthermore, $H_\beta(z)$ may be calculated just using *ZOH* in the following way,

where $h_o(s) = \dfrac{1 - e^{-sT}}{s}$ is the transfer function of a *ZOH* and T is the sampling time, which allows to calculate the β-discrete version of the continuous time plant when only *ZOH* devices are available. Note that $B_\beta(z)$ depends on β, i.e. a fractional order hold with $\beta \neq 0$ adds a pole at the origin respect to the case $\beta = 0$ and $\delta_\beta = \begin{cases} 1 \, if \, \beta \neq 0 \\ 0 \, if \, \beta = 0 \end{cases}$.

iii. Desired response: model reference

The second order system $G_m(s) = \dfrac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$ is selected to represent the system model reference. This system is characterized by a desired damping ratio of ξ and a natural frequency of ω_n. It is known that small values of ξ would yield short rise time (Kuo 1991). Yet, too small ξ gives a large overshoot and a large settling time. A general accepted range value of ξ for satisfactory performance is between 0.5 and 1, which corresponds to so-called under-damped systems. A damping ratio about $\xi = 0.75$ and a rise time, T_r, equal to four spindle periods is selected for practical applications (Altintas et. al. 1990). The natural frequency corresponds to $\omega_n = 2.5/T_r \, rad/s$ (Kuo 1991).

The authors are carrying out a several study of the system output using differents $\beta - FROH$ holds to obtain the plant and the model reference. Due to extension problems, it will be treated the case which the same $\beta - FROH$ to hold the plant and the model reference is used. Then, in the present section study, $H_{m,\beta}(z) = Z[h_\beta(s) \cdot G_m(s)]$.

B. Adaptive model following controller

The principle of the model following method is to design a set (pair) of controllers in such a way that the poles of the closed-loop system coincides with a prescribed set of desired poles. These poles are designed according to the required performance of a closed loop system.

Two main steps are involved, the estimation of the parameters of the controlled system, i.e the polynomials $A_\beta(z)$ and $B_\beta(z)$, which compose $H_\beta(z) = \dfrac{B_\beta(z)}{A_\beta(z)}$,

and the design process of the controller based on these estimated parameters.

When the model plant is not completely known and/or there is measured noise and/or varies with the time an adaptive model following control strategy allows the programmer to place the poles and zeros. But it is necessary to estimate the plant between changes of the cutting parameters. Then, a recursive least square (RLS) algorithm is used to estimate these parameters. In least square estimation unknown parameters of the linear system explained above are calculated using the following RLS with a forgetting factor, λ, at each sampled period k:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + L(k)\left[F_p(k) - \phi^T(k)\hat{\theta}(k-1)\right]$$

$$L(k) = P(k-1)\phi(k)\left(\lambda + \phi^T(k)P(k-1)\phi(k)\right)^{-1} \qquad (26)$$

$$P(k) = \left(I - L(k)\phi^T(k)\right)P(k-1)\frac{1}{\lambda}$$

where $\hat{\theta}(k)$ is the estimated parameter vector at sample k, $L(k)$ is the estimation gain, $\phi(k)$ is the regression or observation vector, $P(k)$ is the covariance matrix and $\lambda, (0 < \lambda \leq 1)$ is the forgetting factor. When the forgetting factor takes the value of $\lambda = 1$ the estimation algorithm reduces to the least squares standard algorithm. Alternatively, the smaller the λ value gets, the faster forgets the estimation process oldest data. For simplicity, in the simulations it is used $\lambda = 1$.

A pre-compensator and a feedback filter are used to control the plant. The advantages are that the control strategy allows the programmer to place poles and zeros for a unknown plant, with the disadvantage that the control scheme is useless when the system introduces an unstable zero. Thus, the designed control can be applied to inversely stable dicrete systems. The here proposed system introduces a unstable zero of discretization when the $\beta - FROH$ takes $\beta < -0.6$ values. Then, the adaptive control theory has the incovennience that if the unstable zero is unknown it can not be applied.

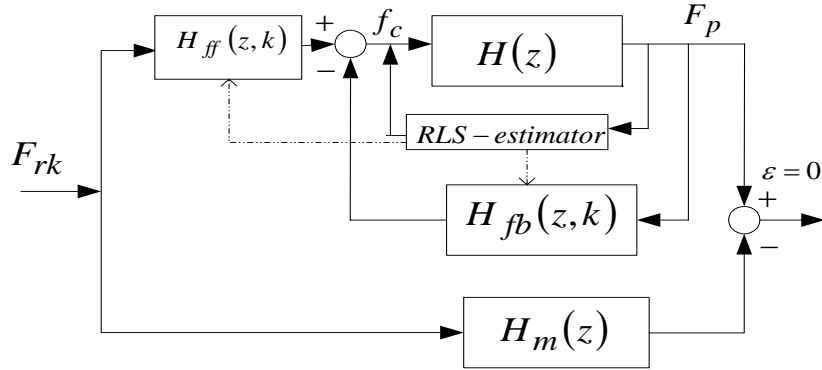The adaptive model following scheme can be depicted by the following block diagram:

Figure 8: Adaptive model following control scheme.

where $H_{ff}(z,k) = \dfrac{S(z,k)}{R(z,k)}$ is the feed-forward filter from the reference signal, $H_{fb}(z,k) = \dfrac{T(z,k)}{R(z,k)}$ is the feedback controller, $H(z)$ is the discrete plant, $H_m(z)$ is the model reference and F_{rk} is the reference force.

The desired performance of the closed loop system is represented by the transfer function, $H_m(z) = \dfrac{B_m(z)}{A_m(z)}$, in which the required poles are included in $A_m(z)$. In order to obtain the desired input-output relation, the filters $H_{fc}(z,k) = \dfrac{T(z,k)}{R(z,k)}$ and $H_{ff}(z,k) = \dfrac{S(z,k)}{R(z,k)}$ must be adjusted, determining the polynomials $T(z,k)$, $R(z,k)$ and $S(z,k)$.

The polynomial $B(z)$ is composed by the stable and monic zeros, $B^+(z)$, and the unstables, $B^-(z)$, in order to cancel the stable zeros of the system closed loop. The model reference zeros is represented by $B_m(z) = B_m^{'}(z) \cdot B^-(z)$.

$T(z,k) = T(z) = B_m^{'}(z) \cdot A_o(z)$ is time invariant since it only depends on the free selected zeros of the reference model which is composed of constant coeficients and $A_o(z)$ is a constant polinomial which is included to ensure good tracking and causality in the design, $R(z,k) = B^+(z) \cdot R^{'}(z,k)$, which is monic.

$T(z), R(z,k)$ and $S(z,k)$ are the unique solutions of degrees,

$$\deg(A_o) \geq 2\deg(A) - \deg(A_m) - \deg(B^+) - 1$$
$$\deg(R) = \deg(A_o) + \deg(A_m) - \deg(A)$$

$$\deg(S) = \deg(A) - 1 \tag{27}$$

$$\deg(T) = \deg(A_o) + \deg(B_m) - \deg(B^-)$$

of the Diophantine equation of polynomials:

$$\hat{A}(z,k) \cdot R'(z,k) + \hat{B}^-(z,k) \cdot S(z,k) = A_m(z) \cdot A_o(z) \tag{28}$$

This leads to design the controller:

$$R(z,k) \cdot f_c(k) = T(z,k) \cdot F_r(k) - S(z,k) \cdot F_p(k) \tag{29}$$

The adaptive model following control will be designed for different cases of the transfer function and reference model obtained from $\beta - FROH$. In the case of sampling with $\beta = 0$, a discrete second order plant is obtained,

$$H_{\beta=0}(z) = \frac{b_o z + b_1}{z^2 + a_1 z + a_2} \tag{30}$$

and a second order model is obatined as a reference,

$$H_{m,\beta=0}(z) = \frac{b_{om} z + b_{1m}}{z^2 + a_{1m} z + a_{2m}} \tag{31}$$

and if $\beta \neq 0$, third order models result,

$$H_{\beta \neq 0}(z) = \frac{b_o z^2 + b_1 z + b_2}{z^3 + a_1 z^2 + a_2 z} \tag{32}$$

and

$$H_{m,\beta \neq 0}(z) = \frac{b_{om} z^2 + b_{1m} z + b_{2m}}{z^3 + a_{1m} z^2 + a_{2m} z} \tag{33}$$

Then, the parameter vector is $\hat{\theta} = \left[\hat{a}_1 \hat{a}_2 \hat{b}_o \hat{b}_1\right]$ if $\beta = 0$, and $\hat{\theta} = \left[\hat{a}_1 \hat{a}_2 \hat{b}_o \hat{b}_1 \hat{b}_2\right]$ if $\beta \neq 0$. Its initial values are set to arbitrary value of $\theta_i(0) = 0.2, \forall i$, where i is the number of estimated parameters for each case.

The regressor vector is namely $\phi(k)$. The covariance matrix $P(k)$ is a square matrix whose dimension is the number of the parameters to be estimate, and it is initialized as diagonal with large equal eigen-values $P(0) = 10^5$. The covariance matrix is reset to its inititial value each time that the estimation error becomes greater than 5% of the reference force (Altintas et. al. 1990) or by monitoring the trace of the covariance matrix (Altintas 2000).

The objective of the control system is to follow a predetermined signal reference, without overshoots. As example, the system response the figures from 9 to 12 are

plotted for the cases of $\beta = -0.3, \beta = 0, \beta = 0.3, \beta = 1,$ respectively. The figures show the model reference and the plant output signal versus sample time, the tracking error signal, $e = (F_p - F_{pm})$, the controller response and the time domain system response. The figures present the resultant force keeping at the reference force, which is set to $1.2KN$. The system registers large overshots in the transient responses, depending on the β-value, and when the axial depth of cut change abruptly.

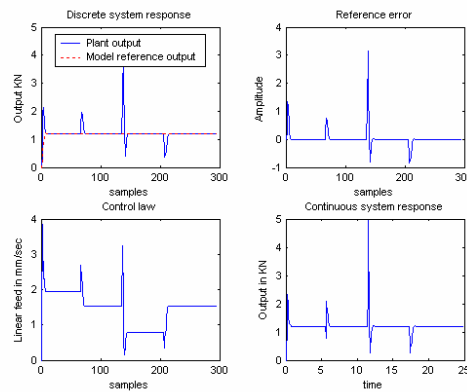Figure 9: Discrete and continuos responses, tracking error, and programmed control law using a $\beta = -0.3$- FROH, with $\theta_i(0) = 0.2$.
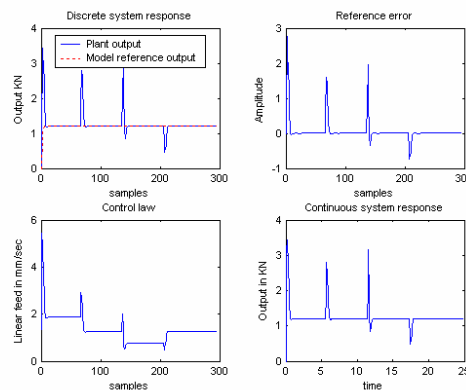

Figure 10: Discrete and continuos responses, tracking error, and programmed control law using a $\beta = 0$- FROH, with $\theta_i(0) = 0.2$..

The transient responses are relied on the initial values of the parameter vector. If those values are near to real values of the plant, the transient response of the milling system will be smooth and feasible. In contrast, if the initial value of the parameter vector has been selected in arbitrary manner the transient is normally oscillated with great maximum overshot and large setting time, leading to damage or even, break the tool (Altintas 1992 and Altintas et. al. 1988).

An accurate transfer function representation of the machining process help the controller designer to have a succesfull implemetation, in the sense that the system transient behaviour is smooth and feasible.
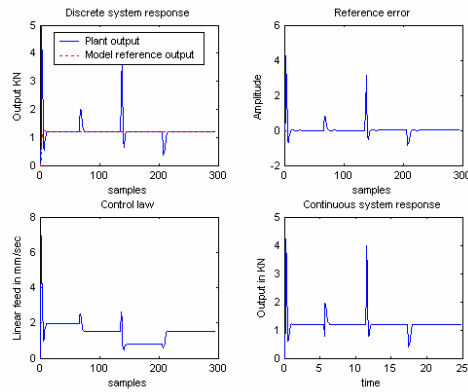

Figure 11: Discrete and continuos responses, tracking error, and programmed control law using a $\beta = 0.3$ - FROH, with $\theta_i(0) = 0.2$.
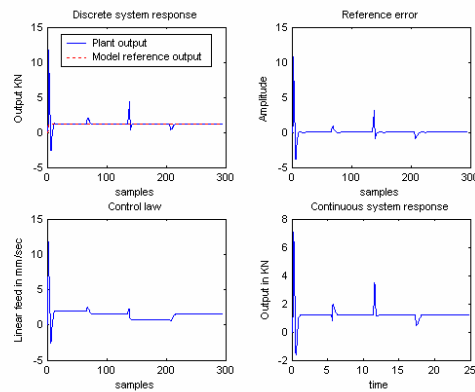

Figure 12: Discrete and continuos responses, tracking error, and programmed control law using a $\beta = 1$ - FROH, with $\theta_i = 0.2$.

Nevertheless, in spite of being quite robust and stable, the adaptive algorithm encountered large output overshots during dangerous step changes of the axial depth of cut. It is because of the intrinsic structure of the closed-loop output. For this reason, if the reference force is selected near to the tool breakage limit, the large overshot lead to break the tool. To avoid this fact, in Spence & Altintas 1998 is proposed to use a CAD assisted force which is introduced when the axial depth of cut changes to minimize the problem. The only thing they need to know a priori information about the work-piece geometry changes to design a successful adaptive control.

The $\beta - FROH$ provides a extra degree of freedom. Selecting appropiately the β-value, better transient response behavior will be achieved. Also, less overshots

betweeen dangerous changes in the axial depth of cut could be obtained. Then, this parameter can be tuned to damp large overshots, such transient responses as between changes in the axial depth of cut. To analyze and compare system responses under differents $\beta - FROH$ discretizations, a cost function is defined:

$$Jc(\beta,T) = \int_0^T \left| F_p(t) - F_{p,\beta}^m(t) \right| dt \cong \sum_{j=1}^{T_0 N_p} \left| F_p(jT_0) - F_{p,\beta}^m(jT_0) \right| \cdot T_0 \cong$$

$$\cong \int_0^{T_p} \left| F_p(\tau) - F_{p,\beta}^m(\tau) \right| dt \tag{34}$$

where F_p is the continuous time domain response, $F_{p,\beta}^m$ is the discrete response with a linear interpolation, T is the sampled time, T_o is the discretized time of the computer, T_p is the tested time and N_p is the samples number of the T_o period over T_p. The cost function calculates an approximation of the area between the time domain response and the linear interpolation of the discrete response. The smaller the area is the better output response will be respect to system overshoots.
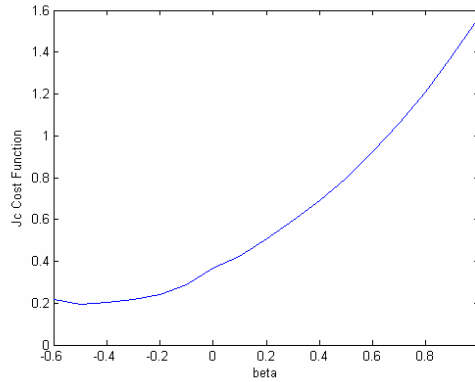

Figure 13 : Cost function, Jc, versus $\beta -$ value

The figure 13 shows the value of the cost function, J_c, for the range of β where the sytem has stable zeros. It can be seen for a β about -0.3, the value of the cost function is minimum and the transient behavior has less overshoot. This fact can be checked in figures from 9 to 12.

Note that the programmed feed rates in case of using a $\beta - FROH$ or using a ZOH for discretizasing the milling system are not the same, see figures 9 and 10. Forced feed rates can also be lead to tool failure or breakage (Altintas 1992).

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5.   Conclusions

In this chapter, an effective method to select an appropiate set of cutting parameters which allow to avoid the chatter effect in milling operations is proposed. The advantage of this method is its simplicity for being implemented in comparison with standard techniques appearing in the literature which involve complex analytical procedures or, in some cases, heuristic tools available only for particular situations. In this way, an expert system based approach is presented. The expert system codifies the correct system operation into rules taking into account not only the potential presence of chatter and its avoidance, but also an improved machine working through an optimality criterion. Furthermore, some robustness in the machining operation against spindle speed variation, and other non-modelled effects such as tool wear and burr formation is also taken into account through the incorporation of operation margins. By using this set of defined rules, the expert system is capable of selecting the most adequate set of cutting parameter values preventing chattering while guaranteeing stability and providing an optimal behaviour. Furthermore, when several tools are available to perform the same operation, the expert system is able to select the most appropriate one depending the optimality criterion chosen. This conceptually simple approach allows to be effectively implemented by workers not especially experienced in advanced milling operations. Moreover, having selected the set of cutting parameters, an adaptive controller scheme has been proposed to deal with time-varying and unknown system parameters. The novelty of the control scheme relies on the use of a FROH instead of the usual ZOH appearing in the literature. The introduction of an additional degree of freedom in the discretization process allows to improve the transient response behaviour of the continuous closed-loop system by an adequate selection of the fractional order gain as simulation results have pointed out. Furthermore, the utilization of FROHs seems to be a promising way to overcome other control limitations which could appear in the control design process, such as the presence of unstable plant zeros, leading to a wider application of control design procedures. In addition, the general FROH hold can be implemented by means of ZOH holds, which make this approach fairly feasible to be implemented in the manufacturing industry.

6.   Future Research

The future research work can be considered to be twofold. Firstly, the development of a more general expert system definition, which allows taking into account a greater number of effects including, for instance, surface finishing, along with its integration with classical control systems. Moreover, since the use of FROH has

revealed to be a powerful tool to deal with some drawbacks and limitations of control system designs, the second research line is aimed at incorporating this discretization technique to address in an integrated way the problems of improving transient responses, the reduction of continuous-time output oscillations between sampling instants and the improvement of the stability of the zeros of the discretized system. These objectives compete for an optimal beta whose value will finally result as a trade-off between the desired importance of each one of these factors.

7.   References

Altintas, Y., Yellowley, I. & Tlusty, J. (1988). The detection of Tool Breakage in Milling Operations. Journal of Engineering for Industry. Vol. 110, August 1988, pp. 271-277.

Altintas, Y., Sassani, F. & Ordubadi, F. (1990). Design and Analysis of Adaptive Controllers for Milling Process. Transactions of the CSME. Vol. 14, No. 1/2, pp. 17-25.

Altintas, Y. (1992). Prediction of Cutting Forces and Tool Breakage in Milling from Feed Drive Current Measurements. Journal of Engineering for Industry, Vol. 114, November 1992, pp.386-392.

Altintas, Y. & Chan, P.K. (1992). In Process Detection and Suppression of Chatter in Milling with Variable Spindle Speed. International Journal of Machine Tools and Manufacture. Vol. 32, No.2, 1992, pp. 329-347.

Altintas, Y. (2000). Manufacturing Automation. Cambridge University Press.

Bilbao-Guillerma, A., De la Sen, M. & Alonso-Quesada, S. (2005). On a Root Locus-based Analysis of the Limiting Zeros of Plants of Nominal Order at most two under FROH-discretization. Proceedings of the 2005 American Control Conference.

Budak, E. & Altintas, Y. (1998) Analytical Prediction of Chatter Stability in Milling - Part I: General Formulation & Part II: General Formulation to Common Milling Systems. Journal of Dynamic Systems, Measurement and Control. Vol. 120, March 1998, pp.22-36.

Campomanes, M. L. & Altintas, Y. (2003). An improved time domain simulation for Dynamic Milling at Small Radial Immersions. Journal of Manufacturing Science and Engineering, Vol. 125, August 2003, pp. 416-422.

Delio, T., Tlusty, J. & Smith, S. (1992). Use of audio signals for chatter detection and control. Journal of Engineering for Industry. Vol. 114, May 1992, pp.146-157.

Dohner, J.L., Lauffer, J.P.,Hinnerichs, T.D., Shankar, N., Regelbrugge, M.,Kwan, C., Xu, R., Winterbauer, B. & Bridger, K. (2004) Mitigation of chatter

Instabilities in milling by active structural control. Journal of Sound and Vibration, Vol. 269, 2004, pp. 197-211.

Elbestawi, M.A., Mohamed, Y. & Liu, L. (1990). Journal of Dynamic Systems, Measurement and Control, Vol. 112, Dec. 1990, pp. 611-617.

Ganguli, A. (2005). Chatter reduction through active vibration damping. Ph. D. Dissertation. Active Structures Laboratory, Department of Mechanical Engineering & Robotics. Université Libre de Bruxelles. November 2005.

Insperger, T., Schmitz, T.L, Burns, T.J. & Stépán, G. (2003). Comparison of Analytical and Numerical Simulations for Variable Spindle Speed Turning. Proceedings of IMECE´03: 2003 ASME International Mechanical Engineering Congress, November 16-21, 2003, Washington, D.C., U.S.A.

Jayaram, S., Kapoor, S.G. & DeVor, R.E. (2000). Analytical Stability Analysis of Variable Spindle Speed Machining. Journal of Manufacturing Science and Engineering, Vol. 122, (August 2000), (pp. 391-397).

Koenigsberger, A. & Sabberwal, S. (1961). An Investigation into the cutting force pulsations during milling operations. International Journal of Machine Tool Design and Research, Vol.1, 1961.

Koren, Y. (1983). Computer Control of Manufacturing System. McGraw-Hill, N.Y.

Koren, Y. (1997). Control of Machine Tools. Journal of Manufacturing Science and Engineering. Vol. 119, November 1997, pp. 749-755.

Kuo, B.C. (1991). Automatic Control Systems, Prentice-Hall, Englewood Cliffs, New Jersey, 1991.

Landers, R.G. (1997). Supervisory Machining Control: A Design Approach Plus Force Control and Chatter Analysis Components, Ph. D. Dissertation, Department of Mechanical Engineering and Applied Mechanics, University of Michigan, Ann Arbor, 1997.

Landers, R.G., Ulsoy, A.G., and Furness, R.J. (2002). Process Monitoring and Control of Machining Operations. Mechanical Systems Design Handbook. CRC Press, Chapter 6, 2002, pp. 85–119.

Landers, R.G. (2005), Regenerative Chatter in Machine Tools, Vibration and Shock Handbook, C.W.DeSilva (ed.), CRC Press, Chapter 35.

Li, H. & Li, X. (2000). Modelling and simulation of chatter in milling using a predictive force model. International Journal of Machine Tools & Manufacture, Vol. 40, 2000, pp. 2047-2071.

Li, H. Z., Li, X. P. & Chen X. Q, (2003). A novel stability criterion for the modelling and simulation of the dynamic milling process in the time domain. International Journal of Advanced Manufacturing Technologic, Vol. 22, July 2003, pp. 619-625.

Merrit, H.E. (1965). Theory of Self-Excited Machine-Tool Chatter. Journal of Engineering for Industry, Vol. 87, 1965, pp. 447-453.

Michiels, V.; Van Assche, V. & Niculescu, S. (2005). Stabilization of Time-Delay Systems With a Controlled Time-Varying Delay and Applications. IEEE Transactions on Automatic Control, Vol. 50, No.4,April 2005,pp.493-504.

Peng, Y.H. (2004). On the performance enhancement of self-tuning adaptive control for time-varying machining processes. International Journal of Advanced Manufacturing Technology, Vol. 24, 2004, pp. 395-403.

Ralston, P.A. & Ward, T.L. (1988). Adaptive Control of Machine Tools: the past and Projected role of Numerical Control Computers. Computers and Industrial Engineering. Vol. 14, No. 2, 1988, pp. 85-94.

Sastry, S., Kapoor, S.G., DeVor, R.E. & Dullerud, G.E. (2001). Chatter Stability Analysis of Variable Speed Face Milling Process. Journal of Manufacturing Science and Engineering, Vol. 123, (November 2001), (pp. 753-756).

Segalman, D. & Redmond, J. (1996). Chatter suppression through variable impedance and smart fluids.Proceedings of the SPIE,2721(1996),pp.353-363.

Smith, S. & Tlusty, J. (1991). An overview of Modelling and Simulation of the Milling Process. Journal of Engineering for Industry. Vol. 113, May 1991, pp. 169-175.

Smith, S. & Tlusty, J. (1992). Stabilizing Chatter by Automatic Spindle Speed Regulation. Annals of the CIRP. Vol. 41, No. 1, 1992, pp. 433-436.

Smith, S. & Tlusty, J. (1993). Efficient Simulation Programs for Chatter in Milling. Annals of the CIRP. Vol. 42, No. 1, 1993, pp. 463-466.

Spence, A. & Altintas, Y. (1991). CAD Assisted Control for Milling. Journal of Dynamic Systems , Measurement and Control. Vol. 113, September 1991, pp. 444-450.

Tomizuka, M. (1983). Model reference adaptive control of the milling process. Control of Manufacturing Processes and Robotics Systems, 1983, pp.55-63.

Wang, M. & Fei, R. (1999). Chatter suppression based on nonlinear vibration characteristic of electrorheological fluids. International Journal of Machine Tools & Manufacture. Vol. 39, 1999, pp.1925-1934.

Wiercigroch, M. & Budak, E. (2001). Sources of non-linarities, chatter generation and suppression in metal cutting. Philosophical Transactions of the Royal Society of London. Vol.359, 2001, pp. 663-693.

Wong, S.V. & Hamouda, M.S. (2003). The development of an online knowledge-based expert system for machinability data selection. Knowledge-Based Systems. Vol. 16, 2003, pp.215-219.

Ulsoy, A.G. & Koren, Y. (1989). Applications of Adaptive Control to Machine Tool Process Control.IEEE Control Systems Magazine,June 1989, pp. 33-37.

Tobias, S.A. (1965). Machine Tool Vibrations. Ed. Verlag, 1965.