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Original Citation

Rubio Rodriguez, Luis and De la Sen Parte, Manuel (2007) Optimization rules for mill cutter and cutting parameters selection incorporating a control algorithm. In: Proceedings of Emerging Technologies and Factory Automation,. ETFA 2007 . IEEE, Patras, Greece, pp. 1421-1424.

This version is available at http://eprints.hud.ac.uk/id/eprint/16086/

Optimization rules for mill cutter and cutting parameters selection incorporating a control algorithm

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Abstract— In this paper an optimization procedure has been developed in order to select mill cutter and cutting parameters. For the purpose a cost function, which compares system performance, is contrived. An example is presented to illustrate the method.

I. INTRODUCTION

The selection of adequate tools and cutting parameters in machine tool environments has increased attention during the last years. The increased competence makes to plan thoroughly machining conditions in order to minimize costs and improve the final product [1].

This paper brings forward the concept of selecting an appropriate mill cutter, among a known set of candidate cutters, while obtaining the adequate cutting parameters for milling operations through an optimization algorithm.

The knowledge-base defines the allowable cutting parameters, given by the pairs spindle speed and axial depth of cut under the border line in the stability chars, and the feed velocity rate, which is used as control signal, is restricted by the control law. The triple axial depth of cut, spindle speed and feed velocity rate which fulfill control and stability restrictions conform the cutting space parameter, by taking into account the spindle power availability.

On the other hand, a novel cost function is designed, it hangs on spindle power consumption, material removing rate, a stability margin against possible perturbations in the spindle speed and the tracking error signal.

The Material Remove Rate (MRR) represents the amount of material to be removed from the work-piece, this parameter measures the efficiency of the removal process. It is required to be as large as possible, but the occurrence of machine tool vibrations limits this parameter. Another variable which limits the process effectiveness is the power available in the spindle motor. The third parameter taking part into the cost function is considered to ensure a well-posed behavior of the system if a perturbation in the spindle speed happened. Finally, the last parameter is an indicator of how well the milling forces track the reference one in order to avoid tool breakage and to achieve certain degree of quality in the finishing of the working-piece.

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

II. SYSTEM DESCRIPTION

The standard milling system is described as a second order differential equation such as typical mechanical systems. The system is excited by the cutting force $F(t)$. Then, the equation of motion has the form [2,3]

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

where $r(t) = \{x(t) \quad y(t)\}^T$, $F(t) = \{F_x(t) \quad F_y(t)\}^T$, M, B and C are the modal mass, damping and stiffness matrices.

The milling cutting force is denoted by a tangential force proportional with the instantaneous chip thickness, and a radial force which is expressed in terms of the tangential force [2,3].

$$F_t(t) = a_{dc} \cdot K_t \cdot t_c(t); F_r(t) = K_r \cdot F_t(t) \tag{2}$$

K_t, K_r are specific cutting constants of the material, $t_c(t)$ is the chip thickness and a_{dc} is the axial depth of cut.

The chip thickness consists of a static part and a dynamic one. The static part is proportional to the feed rate, and it is attributed to the rigid body motion of the cutter. The dynamic part models two subsequent passes of the tool through the same part of the work-piece [2,3].

$$t_c(t) = f_r \cdot \sin\phi_j + [x(t-\tau) - x(t)] \cdot \sin\phi_j + [y(t-\tau) - y(t)] \cdot \cos\phi_j \tag{3}$$

where f_r is the feed rate and τ is the delayed term defined as $\tau = 60/N_t \cdot S_s$, N_t is the number of teeth and S_s the spindle speed. The resulted equation corresponds with a second order delay differential equation with time varying parameters. It can be solved numerically [2] or analytically, using some approximations [3]. The solution of the equation in the parameters space yields to the well-known stability lobes [2,3]. Uncertainties in the cutting process, the force-feed nonlinearity inherent in the metal cutting process, and fulfil machine requirements, such as avoid tool wear and tool breakage, achieve certain degree of quality in surface finish or save machining time and cost can be accommodated using a control strategy. Then, a continuous transfer function which relate both signals, measured resultant force and the actual feed delivered by the drive motors can be modelled as a first order dynamics [3], in chatter and resonant free zones,

$$G_p(s) = \frac{F_p(s)}{f_a(s)} = \frac{K_c a_{dc} r(\phi_{st}, \phi_{ex}, N_t)}{N_t \cdot S_s} \frac{1}{\tau_c s + 1} \tag{4}$$

where $K_c \ (N/mm^2)$ is the cutting pressure constant, $a_{dc} \ (mm)$ is the axial depth of cut, $r(\phi_{st}, \phi_{ex}, N)$ is a non-dimensional immersion function N_t is the number of teeth on the milling cutter and $S_s (rev/s)$ is the spindle speed. Furthermore, it is desired to take into account the control dynamics in order to have a more accurate system. In this way, the machine tool control and drive system can be approximated as a first order system [3],

$$G_s(s) = \frac{f_a(s)}{f_c(s)} = \frac{1}{\tau_s s + 1} \tag{5}$$

where f_a and f_c are the actual and command velocity values of the table in (mm/s) respectively and τ_s is an average time constant, which depends on the type of the machine tool. In this study, it is assumed to be 0.1 ms.

From (5) and (6), the combined transfer function of the system,

$$G_c(s) = \frac{F_p(s)}{f_c(s)} = \frac{B_c(s)}{A_c(s)} = \frac{K_p}{(\tau_s s + 1)(\tau_c s + 1)}$$

(6)

being the process gain $K_p \ (N \cdot s/mm) = K_c a_{dc} r / N_t S_s$.

III. RULES

The following algorithmic methodologies are used as *preliminary rules* to have a more robust system,

Rule 1: Stability margin setting of the knowledge-base to ensure that the system plays in a stable region, despite the system model uncertainties. It is composed of two parts.

Rule 1.1: In order to calculate secure stability lobes char, a small accurate stability margin is prescribed, i.e, it is supposed that the chatter vibrations happen at $\delta + i \cdot \omega$, instead of at $i \cdot \omega$. The reason is that the stability border line is calculated from a linear approximation [8] so that the nominal stability frontier and its neighborhood are inaccurate as stable regions of the real nonlinear problem. Then, $i \cdot \omega$ is replace by $\delta + i \cdot \omega, \delta > 0$, when the stability border line is calculated (see [6]).

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. Then, the limited axial depth of cut is programmed with a confine on this parameter; $a_{dc,\lim} = \alpha \cdot a_{dc,\lim} \ 0 < \alpha < 1$. This rule lets a better control capacity in the spindle speed. On the other hand, a better MRR selection is lost.

Rule 2: For searching the allowable input parameter space, the set of spindle speed and axial depth of cut, the following rule methodology, consisting of two differentiated parts, is applied.

Rule 2.1: Calculate the boundary points, spindle speed and axial depth of cut pairs, which compose the border line between stable and unstable zones, satisfying rule 1. This rule is obtaining by plotting the stability lobes char, which gives the border line between stable and unstable zones.

Rule 2.2: Calculate the admissible input space, subjected to control and spindle motor power availability restrictions.

2.2.1: Control restrictions: The main control restriction is to maintain the forces below a prescribed safety upper bound. This fact ensure avoiding or minimizing tool wear and tool breakage, save machining times and achieve certain degree of quality in finishing the surface on the work-piece. In this way, it is required that the force follows to a constant reference signal. Since the milling plant parameters are unknown and/or time varying, adaptive techniques are used in order to control milling forces. In this paper model reference adaptive control is used to retain the force signal at the reference signal. Then, the control scheme of the figure is scheduled in order to achieve force reference requirements. More detailed explanation of the discrete-time control scheme can be found in references [3]. The continuous transfer function is discretized under a zero order hold (ZOH),

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

(8)

The continuous model reference is chosen to be $G_m(s) = \frac{\omega_n^2}{s^2 + 2 \cdot \xi \cdot \omega_n \cdot s + \omega_n^2}$, with $\xi = 0.75$, $\omega_n = \frac{2.5}{T_r}$, being T_r, the rise time, equal to four spindle periods is usually selected for practical applications [3].

The aim of the model-following control strategy is to force the closed-loop system to behave as a prescribed reference model. Recursive least-squares estimation algorithm is used in order to identify plant parameters.

Perfect matching is achieved through the control signal:

$$f_{c,k} = \frac{T}{R_k} \cdot F_{r,k} - \frac{S_k}{R_k} \cdot F_{p,k}$$

(7)

where $H_{ff}(z,k) = \frac{T(z)}{R(z,k)}$ and $H_{fb}(z,k) = \frac{S(z,k)}{R(z,k)}$.

2.2.2: Spindle Power availability constraints: The power draws from the spindle motor constraints the machining efficiency. It is found from, $P_t = \pi \cdot D \cdot S_s \cdot F_t$, where D is the tool diameter, S_s is the spindle speed and F_t is the tangential force. Since F_p is the resultant cutting force, $F_p = \sqrt{F_t^2 + F_n^2}$, and $F_n = K_n \cdot F_t$, and the power draws from spindle motor is calculated.

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 among the candidates though the optimization rules, explained below. Then, the study requires a given set of candidates milling cutters characterized by the following set of parameters:

$$R_i = (\omega_{nx}, \omega_{ny}, \xi_{xi}, \xi_{yi}, k_{xi}, N_{ti}, D_i, \beta_i)$$

where the pair $(\omega_{xi}, \omega_{yi}) \in \omega$ represents 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, and N_{ti}, D_i and β_i characterize the number of teeth, the diameter and the tool helix angle, respectively. $R_i \in T$, $i = 1, 2 \ldots n$, where n is the number of tools and T the set of tools available to the designer. ω, ξ and k represent the set of tools´ natural frequencies, damping ratio and static stiffness, respectively. Each one is conformed by the pairs $(\omega_x, \omega_y), (\xi_x, \xi_y)$ and (k_x, k_y) for each tool.

1) Tool cost model definition

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

$$C(P_t, MRR, \Delta S_s, e_t; R, c_1, c_2, c_3, c_4) = c_1 \cdot NF_1 \cdot P_t + c_2 \cdot \frac{NF_2}{MRR} + c_3 \cdot \frac{NF_3}{\Delta S_s} + c_4 \cdot NF_4 \cdot e_t$$

(8)

$$\text{with} \sum_{i=1}^{4} c_i = 1 , \ R \in T .$$

The cost function is composed by the following terms:

- *Material Remove Rate*, $MRR = a_{dc} \cdot r_{dc} \cdot f_r \cdot S_s \cdot N_t$, where a_{dc} is the axial depth of cut, r_{dc} the radial depth of cut, f_r is the linear feed rate, S_s the spindle speed and N_t the number of teeth.

- *Cutting Power draw from the spindle speed*, $P_t = V \cdot F_t$, where $V = \pi \cdot a_{dc} \cdot t_c$, where t_c is the chip thickness, and the tangential force, F_t, is obtained from the measured cutting force, F_p.

- *Spindle Speed security change*, ΔS_s, it is an additional term added to the cost function model to be sure that chatter vibrations are avoided. The spindle speed security change measures the nearest spindle speed at which chatter vibrations happen. This fact allows to have an error margin due to possible perturbations in this variable. To calculate analytically ΔS_s, previous work of the authors is referred [4].

- *Tracking error signal*, e_t, which gives measurements in the control constraints.

Standardizing factors are added to the cost function in order to equalize the magnitude of the various terms in the cost function. 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 vibration and spindle power restrictions calculated among all the candidate cutters, $NF_3 = \Delta S_{s,max}$, where $\Delta S_{s,max}$ is the maximum measured value of this variable among the candidate cutters and $NF_4 = e_{t,max}$, where $e_{t,max}$ is the maximum error tracking assessed among the candidate cutters.

Finally, the c_i, $i = 1, .., 4$, values are the weights of the cost function terms. They measure the importance of the cost function terms.

2) Optimization rules

The above defined tool cost function is used to select the appropriate tool and cutting parameters by selecting an optimal operation point, the selection of the pair, tool, operation point, is performed in a integrated way through the following optimization rules.

Rule 3: *Weight factors selection*

The weighting factors (c_i) are intended to be programmed by the machine operator and have the restriction to sum one. An extended explanation of their meaning and their adequate selection is given in this section. To select suitable values of c_i, $i = 1, .., 4$, their meaning has to be perceived. The c_1 measures the importance of the spindle power consumption. The larger the c_1 is, the more important to the spindle power consumption in the cost model function will be. 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 can be applied to the c_3, which measures the stability against possible perturbations in the spindle speed variable. Finally, the c_4 -constant governs avoiding tool breakage, achieve certain degree of quality on work-piece surface finishing and save machining production times and costs through the measurement of the tracking error signal in the adaptive control scheme of the milling process.

Rule 4: *Tool selection criterion*

A simple tool selection criterion has been developed. For a given values of c_i, 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 saved. The procedure is repeated for all the available cutters.

Comparing the minimum value of the cost function for all the 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**

$C\left(P_{tj}(q_j), MRR(q_j), \Delta S_{s,j}(q_j), e_{t,j}(q_j); R_k, c_i\right)$ for each $R_k \in T_k$, $k \in \overline{N}$, $\overline{N}$ is the given set of candidate tools and $\forall q_j \equiv (S_{s,j}, a_{dcj}, f_{r,j}) \in Q$ where $j \in \overline{N}_P = \{1, .., N_p\}_p$; $p \in \overline{N}$ (denoting that each machine can be potentially tested for distinct testing operating points) is a discrete subspace of the cutting parameters space where the cost function is calculated.

- For obtaining the selected tool, ST, **compute**

$$ST = \arg\min_{i \in N}\left\{C\left(P_t(q_j), MRR(q_j), \Delta S_s(q_j), e_t(q_j); R_k, c_i\right)\right\} \quad (9)$$

with $ST \in T$, obtaining the appropriate tool according to the criterion. Following the rules, the expert system provides an appropriate tool among the candidates.

Rule 5: *Cutting parameter selection*

- **Rule 5.1**: *Cutting selection*

To select the cutting parameters, there are two possibilities. First of all, directly, calculate the cutting parameters, which correspond to the selected tool, which gives the minimum value of the cost function. It can be expressed mathematically as,

Compute the following equation (10),

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

obtaining an input cutting parameter for the selected tool. The cutting parameter space is obtained by checking all possible values of spindle speed and axial depth of cut which are below the stability line according to Rule 1. These values join to the allowable feed rates, given by spindle power consumption restriction and control requirements conform the cutting space parameter. Then, for the selected tool, the triple of cutting parameters which minimize the cost function, are selected.

- **Rule 5.2**: *Refined cutting selection*

In order to have a more accurate possibility, it has been taken into consideration that the cutting parameters can be searched with a more fine integration step around the point where the cost function gives its minimum value. Now, the cutting parameter space is given by a 3-tuple $Q^* = \left(S_s^{(k)*}, a_{dc}^{(k)*}, f_r^{(k)*}\right)$ around q^*, for $k = 1, .., p$, where p is the number of points to be considered, according to rules 1 and 2. The procedure for obtaining the required cutting parameters is the same as used in Rule 5.1 through equation (10) for the above defined new cutting parameters.

Mathematically expressed,

Compute,

$$q^{**} = \arg\min_{q^{*(k)} \in Q^*}\left\{C\left(P_t(q^{*(k)}), MRR(q^{*(k)}), \Delta S_s(q^{*(k)}), e_t(q^{*(k)}), ST, c_i\right)\right\} (11)$$

In this way, the refined cutting parameters are obtained.

Rule 6: *Tuning c_i values to prevent process malfunctions.*

Nevertheless, in programming the selected tool and cutting parameters, malfunctions of the process may lead to poor behavior of the process. The most important are tool wear and burr formation. These phenomena, which are common in manufacturing processes, make that the analytical and experimental testes are not always in concordance. If it is

happened, the following algorithmic methodology could be applied,

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

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

IV. EXAMPLE

For the validation of this method, the above study has been applied for two practical straight cutters and full immersion up-milling operation. The example considers the tools to have the following characteristics, according with the section III.B notation, $R_1 = (603, 666, 3.9, 3.5, 5.59, 5.715, 3, 30, 0)$ and

$R_2 = (900, 911, 1.39, 1.38, 0.879, 0.971, 2, 12.7, 0)$.

The natural frequency is in hertz, the tool damping in %, the tool stiffness in $KN \cdot mm^{-1}$ and the diameter of the tool in mm . The work-piece is a rigid aluminum block whose specific cutting energy is chosen to be $K_{t1,2} = 600$ $KN \cdot mm^{-2}$ 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 parameters belong to the expert system take the following values, the stability margin factor, $\delta = 0.05$ and the stability margin factor for the axial depth of cut, $\alpha = 0.95$. The analytical testes for mill cutter selection were conducted using spindle speeds with increments of 1000 rpm , axial cutting depths started with its minimum value in the stability border line divided by ten, with increments of the same size. The spindle motor guarantees 2745.3 W of power.

The resulting tool is that leading to the minimum tool cost function value. A general analysis shows in figure 1, in which the minimum value of the tool cost function for all possible combinations of c_1, c_2, c_3 and $c_4 = 0.4$ with the restriction $c_1 + c_2 + c_3 + c_4 = 1$ is displayed. The analysis has revealed that the first tool has a better behavior than the second for some combinations of the c_i parameters, and vice versa. For the cutting parameters selection, two steps have been done. First, once the tool has been selected, for example, for values of $c_1 = 0.1$, $c_2 = 0.45$, $c_3 = 0.05$ and $c_4 = 0.4$, the cutting parameters corresponding to the minimum of the tool cost function for the selected tool are obtained. In the studied case, these values are $q^* = (1000, 0.1641, 22.843)$.

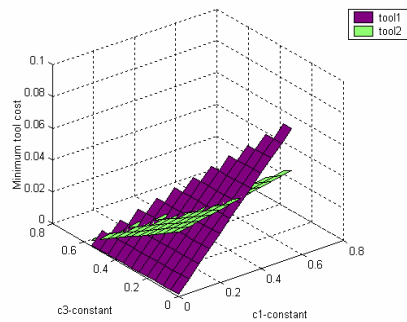Figure 2 shows the situation in the stability lobes of the

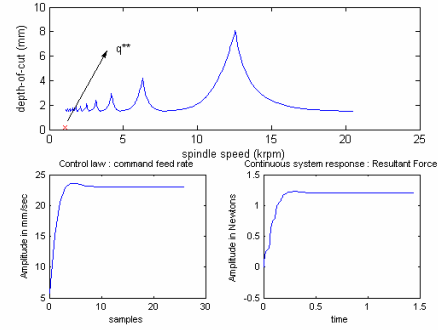Figure 1: Minimum Cost function versus c_1, c_2, c_3 varies and $c_4 = 0.4$

Figure 2: Situation of the point q^{**} in the stability diagram and feed command and resultant force responses with control constraint.

programmed point q^{**} , the control signal or feed command and the continuous force output. It is observed that the point is robustly stable, and the control signal and the output are feasible signals.

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. Moreover, the method can be to schedule the relative compliance between the available tools and the used work-pieces materials. Finally, the developed 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 number of eventual changes of tools.

V. CONCLUSION

An efficient approach for mill cutter and cutting parameters selection has been developed. The developed system is instructed with the characteristics of the candidate tools, as well as with the stability margin and constrains of the operation, such as power availability, robust and control requirements. Furthermore, a tool cost model function, built from a set of preliminary 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 and cutting parameters for the operation which lead to the maximum productivity, while respecting stability, power consumptions margins and control constraints through optimization rules. A simulation example which shows the behavior of the system is presented.

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