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Adaptive Control for Computer Numerical Control (CNC) Milling based on Dynamic Cutting Force Analysis

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***Abstract*—In this work, an adaptive control system has been developed for computer numerical control (CNC) milling based on dynamic force analysis. In an adaptive controlled system, the signals from the offline measurement have to be processed and fed back to the machine tool controller to adjust the cutting parameters. In this paper, the authors present an improved adaptive control system based on dynamic cutting-force model for peripheral milling with helical end mills. The theoretical model is based on the oblique cutting principle and includes the size effect of undeformed chip thickness and the influence of the effective rake angle. A set of closed-form analytical expressions is presented. The simulation results indicate that the improved dynamic cutting-force model does predict the cutting forces in peripheral milling accurately. Using Matlab Simulink simulation results for a number of particular examples are presented.**

Keywords—Machining Process; Adaptive Control; Dynamic Force Analysis; In The Process Monitoring.

1. INTRODUCTION

Condition monitoring is becoming popular in industry because of its efficient role in detecting potential failures. The use of condition monitoring techniques will generally improve plant production availability and reduce downtime cost. A reliable adaptive control system can prevent downtime of the machine or avoid unwanted conditions such as chatter vibration, excessive tool wear by allowing the optimum utilization of the tool life.

In metal cutting, as a result of the cutting motion, the surface of workpiece will be influenced by cutting parameters, cutting force, vibrations, etc. However, the effects of vibrations have been paid less attention.

Prasad et al.[1, 2] presented an investigation for a tool condition monitoring system, which consists of a fast Fourier transform preprocessor for generating features from online acousto-optic emission (AOE) signals to develop database for appropriate decisions.

The drawback of modern computer numerical control (CNC) systems is that the machining parameters, such as feed rate, speed, and depth of cut, are programmed off-line[3].As a result, many CNC systems are inefficient to run under the operating conditions that are far from optimal one.

To ensure the quality of machining products, reduce the machining costs and increase the machining efficiency, it is necessary to adjust the machining parameters in real time to satisfy the optimal machining condition at any given time as per modern condition monitoring strategy [4].

The control of CNC machining processes is presently receiving significant attention due to potential economic benefits associated with automated machining. Control techniques that have been developed for machining traditionally require some form of parameter adaptation. The solution to this problem is adaptive control. An adaptive control system was introduced to the cutting process by Stute and Goetz[5].

The most frequently used systems are model reference adaptive control (MRAC) and self turning regulations (STR). Tomizuka et al.[6] presented investigation on an adaptive model reference adaptive controller approach. These controllers were simulated, evaluated and physically implemented. For effective automization where the process takes place without the interference of the human, continuous monitoring of the machining is necessary. Most frequently, it is materialized by measuring the cutting forces because they contain more information about the process and the tool condition[7]. In spite of initial difficulties in the development, a trend towards equipping the CNC machine with modern adaptive systems can be noticed[8, 9]. The most commonly used adaptive control (AC) systems are adoptive control constraint (ACC) and the constraints implemented in ACC systems are the cutting force, displacement due to vibration, spindle deflection, current, and cutting torque. The operating parameters are usually the feed rate, depth of cut, and spindle speed. Therefore, we would implement on-line adaptive control in conjunction with off-line optimization. In our AC system, the feed rate and depth of cut are adjusted on-line in order to maintain a constant displacement and cutting force in spite of variations in cutting conditions.

The modern market forces the producers to meet the demands of customers. Still accelerating technological progress makes this goal very hard to achieve. The manufacturer must provide product which meet the customers' expectations, while maintaining a satisfactory price both sides. The manufacturing costs has key influence to final price of the product. It is very important to develop new methods of manufacturing cost estimation and improve the existing ones.

Peripheral milling operations are widely used in the automobile, aerospace, textile machinery and other manufacturing industries, where 2D contour parts, i.e. engine components, cams, etc., are milled using complex end-mills. In recent years, due to the need to improve dimensional accuracy of the parts, there has been a push toward reducing the machining errors commonly generated in the milling process. These errors derive from the machine tools, the cutters, the NC programming and the machining process. The errors of the machining process generated in peripheral milling originate from a number of sources, such as tool deflection, workpiece deflection, tool wear, friction, tool run-out, and chatter vibration. Of these, tool deflection due to cutting force is a major problem for precision machining [10].

An accurate dynamic cutting-force model is vital for the precise prediction of tool and workpiece deflection in peripheral milling. Several models based on theoretical assumptions and experimental observations have been developed to predict the cutting forces and were reviewed by Smith and Tlusty [11].

In this paper, the authors present an improved dynamic cutting-force model for peripheral milling with helical end mills. The theoretical model is based on the oblique cutting principle and includes the size effect of undeformed chip thickness and the influence of the effective rake angle.

An excellent style manual for science writers is [7].

2. Fundamental Principles

There are two basic models which are normally used to describe chip formation in metal cutting .

1. Orthogonal cutting. This is characterized by a cutting edge, which is normal, and a chip flow, which is parallel to the direction of tool motion.

2. Oblique cutting. This is characterized by a cutting face, which is inclined by an angle. With respect to the direction of tool motion and by an angle .c between the direction of chip flow and the direction of tool motion.

A. *Geometric Model of Helical End-Mill*

The end-mill can be divided into a number of slices along its z-direction, as shown in Fig. 1(a). Within each slice, the cutting action for an individual tooth can be modelled as for single point oblique cutting, and the tangential and normal cutting forces at any point on the rake face can be obtained from the oblique cutting model. It is important to note here that the tangential and normal directions together with chip thickness vary during the formation of a single chip in milling. Accordingly, a dynamic model must account for these variations in magnitude and direction of cutting forces.

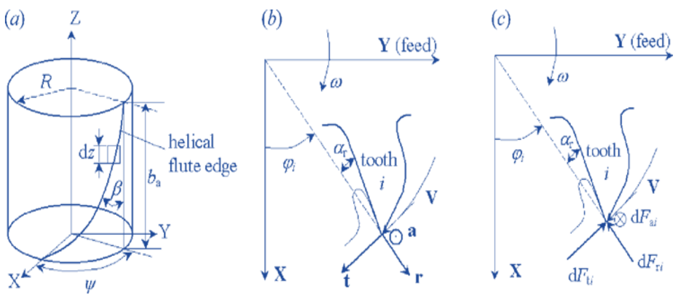

Fig. 1. Geometric model: (a) helical flute edge geometry; (b) curvilinear coordinate system of a tooth element; (c) differential cutting force.

B. *Cutting-Force Model*

The cutting forces acting on the helical flute's rake face are dependent on the undeformed chip thickness. If -l is a portion of the developed cutting edge of elemental length, then dz may be considered as the width of an elemental oblique tool with inclination angleβ,

$$dz = dl\cos\beta. \quad (1)$$

and the differential area of the undeformed chip cross-section

$$dA_v(\varphi_i) = t_i(\varphi_i)dz = t_i(\varphi_i)dl\cos.\ dl = Rd\varphi/\sin\beta \quad (2)$$

Where $t_i(\varphi_i)$ is the undeformed chip thickness.

we get the differential tangential cutting force, as shown in Fig. 1(c), of the peripheral milling:

$$dF_{ti}(\varphi_i) = K_s dA_v(\varphi_i) = K_s t_i(\varphi_i) R\cot\beta d\varphi. \quad (3)$$

where K_s is the tangential cutting-force coefficient, which has the same meaning as the total energy per unit volume u.

Considering the size effect of undeformed chip thickness and the influence of effective rake angle, gives

$$K_s = u_0\left(1 - \frac{\alpha_e - \alpha_{e0}}{100}\right)\left(\frac{h_0}{t_i(\varphi_i)}\right)^{0.2} \quad (4)$$

Where u_0 is the initial total cutting energy per unit volume, α_e (in degrees) is the effective rake face, α_{e0} (in degrees) is the initial effective rake angle, and t_0 is the initial undeformed chip thickness.

To develop the total force applied on the whole cutter, the differential forces are resolved into the feed (y) and normal (x) directions. As the differential cutting-force components are just opposite to the corresponding directions of the curvilinear coordinate system (t, r, a)

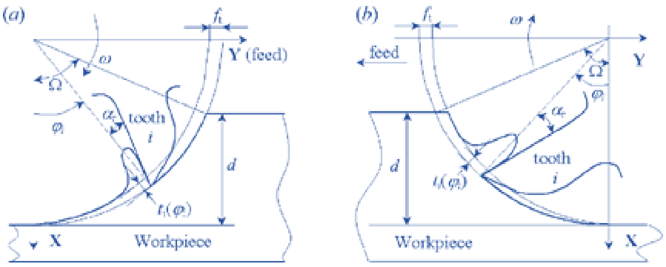

Fig. 2. Peripheral milling method: (a) down-milling; (b) up-milling.

1. *For down-milling:*

$$\begin{cases} F_{ix} \approx -u' f_t R\cot\beta(0.5\varphi_i - 0.25\sin 2\varphi_i + 0.5556\ c\ \sin^{1.8}\varphi_i)\Big|_{\varphi_s}^{\varphi_e} \\ F_{iy} \approx u' f_t R\cot\beta(0.5556\ \sin^{1.8}\varphi_i - 0.5\varphi_i + 0.25\ c\ \sin 2\varphi_i)\Big|_{\varphi_s}^{\varphi_e} \end{cases} \quad (5)$$

Because $0 \le \varphi \le \psi, \varphi_i = \varphi - \omega t + (i-1)(2\pi/m)\ et\ 0 \le \varphi_i \le \Omega$

$$\varphi_s = max\left(0, -\omega t + (i-1)\frac{2\pi}{m}\right) \quad (6)$$

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$$\varphi_e = min\left(\Omega, \psi - \omega t + (i-1)\frac{2\pi}{m}\right) \tag{7}$$

2. For up-milling:

$$\begin{cases} F_{ix} \approx -u' f_t R cot\beta(0.5\xi_i - 0.25 sin2\xi_i - 0.5556\, c\, sin^{1.8}\xi_i)\Big|_{\xi_s}^{\xi_e} \\ F_{iy} \approx -u' f_t R cot\beta(0.5556\, sin^{1.8}\xi_i + 0.5\xi_i - 0.25\, c\, sin2\xi_i)\Big|_{\xi_s}^{\xi_e} \end{cases} \tag{8}$$

Also,

$0 \le \varphi \le \psi, \xi_i = -\varphi + \omega t - (i-1)(2\pi/m)\ et\ 0 \le \xi_i \le \Omega$

Gives the extreme values of the parametric angle .i as

$$\xi_s = max\left(0, -\psi + \omega t - (i-1)\frac{2\pi}{m}\right) \tag{9}$$

$$\xi_e = min\left(\Omega, \omega t - (i-1)\frac{2\pi}{m}\right) \tag{10}$$

Summing up the cutting forces acting on all the m helical flutes gives the total force applied on the whole cutter:

$$\begin{cases} F_x = \sum_{i=1}^{m} F_{ix} \\ F_y = \sum_{i=1}^{m} F_{iy} \end{cases} \tag{11}$$

3. Estimation of Cutting-Force Coefficients

For consistency, we choose the same cutter, workpiece material and cutting conditions (for our simulation) as in the cutting tests conducted by Yucesan and Altintas. These are:

1. Cutter: a single-fluted carbide end-mill with a helix angle
β= 30°, a rake angle α_r = 12° and a diameter of 19.06 mm.
2. Material properties of the carbide cutter: 90% WC, 10% Co, hardness 92 Rockwell.
3. Material properties of the titanium alloy: 6% Al, 4% V, Young's modulus = 110 GPa, Poisson's ratio = 0.34, tensile strength = 900 Mpa.
4. Cutting parameters: axial depth of cut ba= 7.62 mm, radial depth of cut d = 19.06 mm (slotting), ψ = 26.45°,Ω= π, spindle rotation speed n = 500 rpm (cutting speed V = 498.99 mm s^{-1}), with a feedrate ranging from 0.0127 mm per tooth to 0.2030 mm per tooth.

3.1 Diagram of simulation of force Fx and Fy

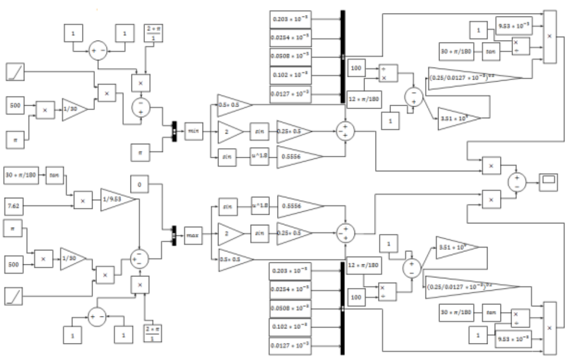

Fig. 3. Diagram by matlab simulink of prediction force Fx and Fy.

After execution we obtain

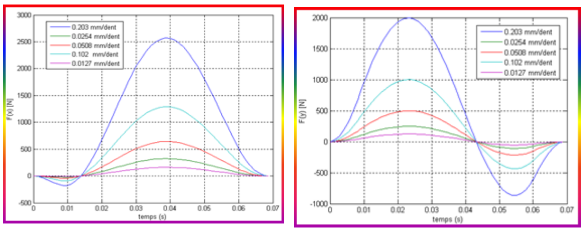

Fig. 4. Predicted cutting forces for a full immersion up-milling test

$m = 1, u_0 = 3.51 * 10^9\, J\, m^{-3}, \quad \alpha_r = 12°, b_a = 7.62\, mm, d = 19.06\, mm, \psi = 26.45°$

This result reveals that when the feedrate is far smaller than the radius of the cutting edge, the ploughing force is dominant and the cutting-force model must be modified.

We will study the influence of the cutting angles, the feed per tooth, the cutter radius on the cutting force and the influence of the axial depth and radial and number teeth on the strawberry on the variation of the cutting force for profile milling (device).

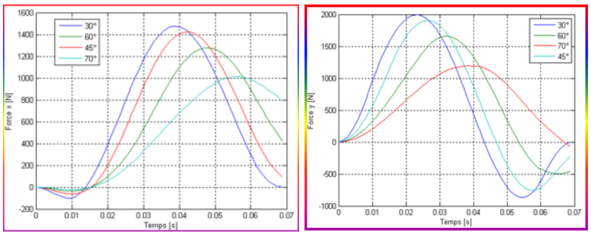

Fig. 5. Influence of angle helice (m=1)

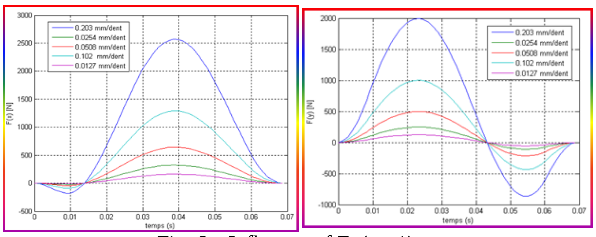

Fig. 6. Influence of Ft (m=1)

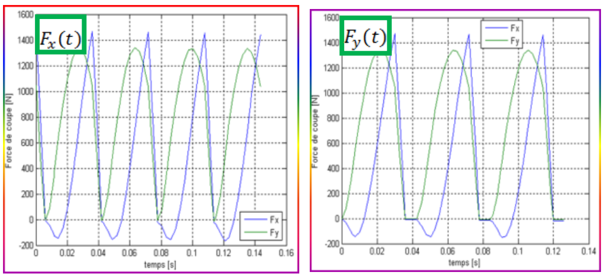

Fig. 7. Influence of nombre of tooth (m=4)

4. CONCLUSION

Manufacturing costs estimation process is very important stage of the design-construction process. The decisions made on this stage has big impact on the product final price.

The series of types manufacturing costs estimation method presented in this paper is based on costs similarity. This method results quality depends on exponents values. The standard values of exponents are known and they are described in many publications. That values were compared to values calculated on the basis of practical simulation of manufacturing process.

The differences between standard and calculated values can be noticed. The standard values assigned to operation should give proper results for every kind of cut type (e. g. rough and finish turning). The values based on simulation result from real situations and they are specified for every type of to cut process. his approach can improve the results accuracy of method based on costs similarity.
and finally this method will help to provide the economic profit of the company.

The research presented here reinforces the size effect of undeformed chip thickness and the influence of the effective rake angle in peripheral milling. Verification results indicate that the model is suitable for general peripheral milling, when the feedrate is larger than the radius of the cutting edge. For fine milling, when the feedrate is smaller than the radius of the cutting edge, the measured cutting force will be greater than the cutting force predicted by the model. This result reveals that the ploughing force is dominant in this condition and the general cutting force model is no longer effective. Case studies reveal that the model may be very effective in reducing the surface form error due to tool deflection if the flute number, the axial depth of cut and the radial depth of cut are selected carefully.

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