Adaptive Dynamic Cutting Force Control Analysis for Peripheral Milling

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ABSTRACT

The implementation of condition monitoring tools can improve plant availability and lower downtime costs in general. A reliable adaptive control system can prevent machine downtime or undesired situations such as chatter vibration and excessive tool wear, permitting the best utilization of a tool's life. This study used dynamic force analysis to create an adaptive dynamic control system for Computer Numerical Control (CNC) milling to adjust a controlled system for signals from offline measurements that will be processed and supplied back to the machine tool controller to correct cutting parameters. This paper describes a better adaptive control system for peripheral milling with helical end mills based on a dynamic cutting force model. This theoretical model is based on the oblique cutting principle and takes into account the effects of the size of undeformed chip thickness and the effective rake angle. Simulation results showed that the enhanced dynamic cutting-force model accurately predicted cutting forces in peripheral milling.

Keywords-machining process; adaptive control; dynamic force analysis

I. INTRODUCTION

Peripheral milling operations are widely used in 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 the dimensional accuracy of the parts, there is a push towards the reduction of the machining errors commonly generated in the milling process. These errors derive from machine tools, cutters, NC programming, and the machining process itself. The errors of the machining process generated in peripheral milling originate from several sources, such as tool deflection, workpiece deflection, tool wear, friction, tool run-out, and chatter vibration. Of all these, tool deflection due to cutting force is a major problem for precision machining [1]. 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 cutting forces [2]. In [3, 4], an investigation was presented for a tool condition monitoring system which consisted of a fast Fourier transform preprocessor for generating features from online Acousto-Optic Emission (AOE) signals to develop a 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 offline [5]. As a result, many CNC systems are inefficient to operate under operating conditions that are far from optimal. To ensure the quality of machining products, reduce machining costs, and increase machining efficiency, it is necessary to adjust the machining parameters in real-time to satisfy the optimal machining conditions at any given time as per modern condition monitoring strategies [6, 7]. The control of CNC machining processes is presently receiving significant attention due to the potential economic benefits associated with automated machining. Control techniques that have been developed for machining traditionally require some form of parameter adaptation, and the solution to this problem is adaptive control. An adaptive control system was introduced to the cutting process in [8].

The most commonly used systems are Model Reference Adaptive Control (MRAC) and Self-Turning Regulations (STR). In [9], an investigation was presented on an adaptive model reference controller approach, simulating, evaluating, and physically implementing it. Continuous monitoring of the machining is necessary for effective automatization where the process takes place without human interference. Most frequently, it is materialized by measuring the cutting forces because they contain more information about the process and the tool condition [10-12]. Despite the initial difficulties in development, a trend towards equipping the CNC machine with modern adaptive systems can be observed [13-15]. The most commonly used Adaptive Control (AC) systems use Adaptive Control Constraint (ACC), with the constraints being the cutting force, displacement due to vibration, spindle deflection, current, and cutting torque. Operating parameters are usually the feed rate, depth of cut, and spindle speed. This study implemented an online adaptive control in conjunction with offline optimization. In this AC system, the feed rate and depth of cut are adjusted online to maintain a constant displacement and cutting force despite variations in cutting conditions.

The modern market forces producers to meet the demands of customers, but the accelerating technological progress still makes this goal very difficult to achieve. The manufacturer must provide a product that meets customers' expectations while maintaining a satisfactory price on both sides. Manufacturing costs have a key influence on the final price of the product, so it is very important to develop new methods to estimate the manufacturing cost and improve the existing ones. This paper presents an improved dynamic cutting-force model for peripheral milling with helical end mills. The theoretical model was based on the oblique cutting principle and included the size effect of undeformed chip thickness and the influence of the effective rake angle.

II. FUNDAMENTAL PRINCIPLES

Two basic models are normally used to describe chip formation in metal cutting:

- Orthogonal cutting, characterized by a normal cutting edge and a chip flow parallel to the direction of tool motion.
- Oblique cutting, characterized by a cutting face inclined by an angle.

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 Figure 1 of [16]. Within each slice, the cutting action for an individual tooth can be modeled 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 that the tangential and normal directions together with chip thickness vary during the formation of a single chip in milling. Consequently, a dynamic model must account for these variations in the magnitude and direction of cutting forces.

B. Cutting-Force Model

The cutting forces acting on the helical flute's rake face depend on the undeformed chip thickness. If dl 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 angle β [16]:

$$dz = dl.\cos\beta \tag{1}$$

and the differential area of the undeformed chip cross-section:

$$\begin{cases} dA_y(\varphi_i) = t_i(\varphi_i)dz = t_i(\varphi_i)dl.\cos\beta \\ dl = Rd\varphi/\sin\beta \end{cases} \tag{2}$$

where $t_i(\varphi_i)$ is the undeformed chip thickness. The differential tangential cutting force of the peripheral milling, as can be seen in Figure 1 of [16]:

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

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:

$$K_s = u_0\left(1 - \frac{\alpha_e - \alpha_{e0}}{100}\right)\left(\frac{t_0}{t_i(\varphi_i)}\right)^{0.2} \tag{4}$$

where u_0 is the initial total cutting energy per unit volume, αe (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. The differential cutting-force components are just opposite to the corresponding directions of the curvilinear coordinate system (t, r, a).

1) For Down-Milling

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

Because:

$$0 \le \varphi \le \psi,\quad \varphi_i = \varphi - \omega t + (i-1)(2\pi/m) \text{ and } 0 \le \varphi_i \le \Omega$$

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

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

2) For Up-Milling:

$$\begin{cases} F_{ix} \approx -u' f_t R\cot\beta\,(0.5\xi_i - 0.25\sin 2\xi_i \\ \qquad -0.5556.c.\sin^{1.8}\xi_i)\Big|_{\xi_s}^{\xi_e} \\ F_{iy} \approx -u' f_t R\cot\beta\,(0.5556\sin^{1.8}\xi_i + 0.5\xi_i \\ \qquad -0.25.c.\sin 2\xi_i)\Big|_{\xi_s}^{\xi_e} \end{cases} \tag{8}$$

Also:

$$0 \le \varphi \le \psi,\quad \xi_i = -\varphi + \omega t - (i-1)(2\pi/m) \text{ and } 0 \le \xi_i \le \Omega$$

gives the extreme values of the parametric angle ξ_i as:

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

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

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

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

III. ESTIMATION OF CUTTING-FORCE COEFFICIENTS

The cutter, workpiece material, and cutting conditions of this study were:

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

IV. RESULTS AND DISCUSSION

This section presents the simulation results in Matlab for a number of particular examples. Figure 1 shows the results of predicting cutting forces for a full immersion up-milling, revealing that when the feed rate is far smaller than the radius of the cutting edge, the ploughing force is dominant and the cutting-force model must be modified.

Figures 2 and 3 show the results on the influence of the cutting angles, feed per tooth, and cutter radius on the cutting force. The values of the instantaneous predicted forces were found as shown in Figure 2 but with different amplitudes. Adjusting the initial total cutting energy per unit of volume and the cutting-force ratio to u_0=2.109Jm^{-3}, c=0.45, the instantaneous predicted forces were obtained, as shown in Figure 3. A comparison of these results with the cutting forces shown in Figure 1 shows that there is a very good agreement. Figure 3 shows that when the feed rate is greater than 0.0254mm per tooth, the predicted cutting forces are very good approximations of the measured cutting forces, and the improved dynamic cutting-force model can be used to predict the cutting forces. However, when the feed rate is less than 0.0254mm per tooth, the predicted cutting forces are smaller than the measured. This reveals that when the feed rate is far smaller than the radius of the cutting edge, the ploughing force is dominant and the cutting-force model must be modified.

V. CONCLUSION

The adaptive dynamic cutting force control analysis estimation process in manufacturing is a very important stage of the design construction process, as the decisions made at this stage have a large impact on the product's final price. This study presented a manufacturing adaptive dynamic cutting force control analysis estimation method based on dynamic force analysis. The quality of the results of this method depends on the exponent values. The standard values of exponents are known and described in many publications. These values were compared to values calculated based on a practical simulation of the manufacturing process. The differences between standard and calculated values can be observed. The standard values assigned to the operation should give proper results for every kind of cut type, e.g. rough and finish. Values based on simulation results from real situations are specified for every type of cutting process. This approach can improve the results accuracy of the proposed method based on cost similarity, and finally, this method could help in securing the economic profit of the company.

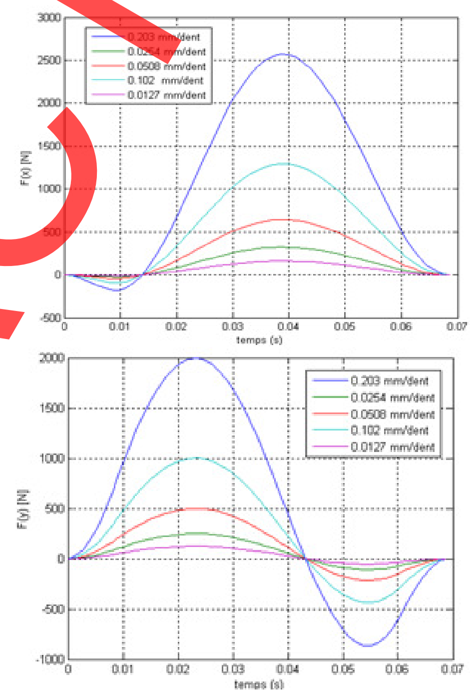

Fig. 1. Predicted cutting forces for a full immersion up-milling test, $m = 1,\ u_0 = 3.51 * 10^9 Jm^{-3},\ \alpha_r = 12°,\ b_a = 7.62mm, d = 19.06mm,\ \psi = 26.45°$.

This study investigated the size effect of undeformed chip thickness and the influence of the effective rake angle in peripheral milling. Verification results showed that the model is suitable for general peripheral milling when the feed rate is greater than the radius of the cutting edge. For fine milling, when the feed rate is less than the radius of the cutting edge, the measured cutting force will be greater than the cutting force predicted by the model. This result shows 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 flute number, axial depth of cut, and radial depth of cut are selected carefully.

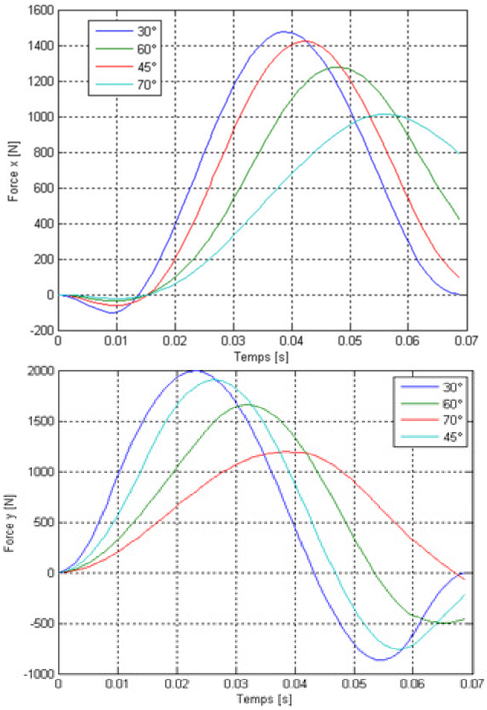

Fig. 2. Influence of angle helice (m=1).

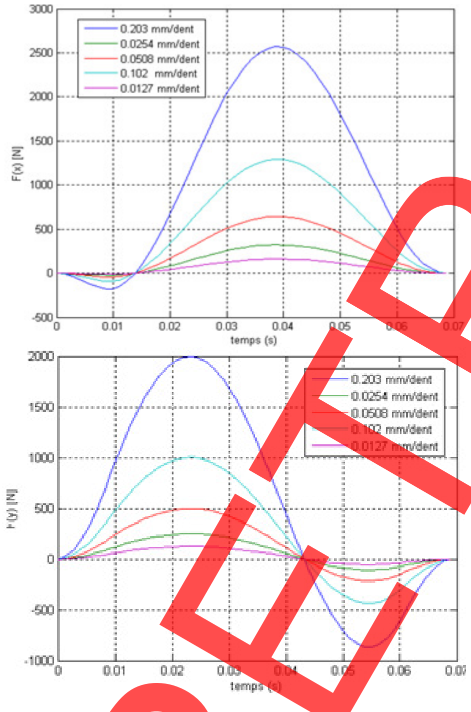

Fig. 3. Influence of Ft (m=1)

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