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DESIGN OF FEEDRATE PROFILE FOR CONSTANT FORCE MILLING INVOLVING VARYING WORKPIECE GEOMETRY

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ABSTRACT

This paper is concerned with feedrate planning for face milling operations involving workpieces of variable geometry and in particular milling over workpieces with existing slots and holes. The objective is the development of a feedrate profile that will maintain a constant average force for the duration of such variable cut, as a means to decreasing the cycle time per workpiece and increasing the process productivity overall.

Torque measurements by a four-component dynamometer was used to estimate runout because of their higher sensitivity to the effective cutting radius. The estimated runout is input to a mechanistic model for face milling to predict cutting forces over slots. The model is inversely solved to give a variable feedrate profile and as such, the average cutting force over slots can be kept near constant. Implementation of the profile in the laboratory concurred favourably with the results of prediction.

INTRODUCTION

The face milling process is widely used in industry for the manufacture of mechanical components and the mechanics of the process have been researched extensively ever since the time of Martellotti's quintessential work (1941 and 1945) on the theory of milling. Emphasis has focused on studying the nature of the process forces as an aid in the design of production machinery that can integrate high metal removal rates with good quality surface finish (Fu, et al. (1984), DeVor, et al. (1984), and Montgomery and Altintas (1991)). An understanding of the force system forms the basis for design against the detrimental effects of deflection, chatter, and vibration in the achievement of these goals (Subbrao et al. (1983)).

A number of more recent studies have also concentrated on designing adaptive force control systems for milling as mechanisms of productivity improvement through the manipulation of the feedrate (Tomizuka, et al. (1983), and Lauderbaugh and Ulsoy, (1989)). The primary objective of these works was to design a controller that would measure the process cutting force and direct the feedrate so as to maintain the force magnitude at a constant level throughout the cutting over different axial depths.

This paper presents a different approach. A mechanistic model for face milling (Fu, et al. (1984)) is used to predict cutting force over slots or holes. Torque measurement instead of force measurement was used to estimate runout that is needed in the prediction model. The torque measurement is more sensitive to the change of effective cutting radius with which runout is closely related. Use is made of an inverse solution to the mechanistic model as the primary means of instigating adjustment in feedrate to achieve constant average resultant force.

EXPERIMENT

A series of experiments were conducted in four stages with the following goals: (1) flycutting tests to develop a database for the determination of empirical constants, (2) multi-tooth full cut cutting tests to determine realistic runout values, (3) multi-tooth cutting tests over slots and holes to verify the nature of resultant average force behaviour for such cuts, and (4) experimental validation of feedrate profile to test that the design of the feedrate profile for milling over slots and holes resulted in a near constant average resultant force over the cut as a whole.

Experiments under eight conditions were carried out by varying cutting speed, feedrate and depth of cut in accordance with a two level factorial design, as shown in Table 1. These conditions were implemented for all tests.

The cutter utilised was a 50 mm diameter Kennametal face mill (50A04R-SS0TP15D) with four insert capability, 0° lead angle, 5° axial rake angle and 0° radial rake angle. Insert type was of a PVC coated grade (TPC W T3 PDTRKC 700) with 0.7 mm nose radius. The material used in all the experiments was mild steel. Force and moment (about z axis) signal was measured via a Kistler Model 9272 four-component dynamometer (Fig. 1). The machining centre used to perform the experiments was a vertical machining centre by Makino, fitted with FANUC-3000C controller. The variable feedrate commands were input directly into the control system in the final experiments.

Fig. 2a depicts the location of the cutter to the workpiece. Entry and exit into the workpiece was at 143.15° and 0° respectively and

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TABLE 1 EXPERIMENT CONDITIONS (2^3 FACTORIAL DESIGN)

Condition	Cutting Speed (R.P.M)	Feed (mm/tooth)	Depth of Cut (mm)
1	560	0.089	0.7
2	560	0.179	0.7
3	1120	0.045	0.7
4	1120	0.089	0.7
5	560	0.089	1.4
6	560	0.179	1.4
7	1120	0.045	1.4
8	1120	0.089	1.4

TABLE 2 EMPIRICAL CONSTANTS FROM FLYCUTTING TESTS

Exp. No.	Average Chip Thickness (mm)	K_t (N/mm^2)		K_r	
		Fitted	Predicted	Fitted	Predicted
1	0.094	3689.9	3416.2	0.589	0.648
2	0.188	3271.7	2983.1	0.407	0.863
3	0.047	4029.0	3912.6	0.678	0.487
4	0.093	3826.4	3416.4	0.578	0.648
5	0.115	3162.6	3285.1	0.842	0.704
6	0.230	2619.4	2868.5	0.672	0.937
7	0.057	3343.6	3762.3	0.991	0.529
8	0.115	3077.7	3285.1	0.820	0.704

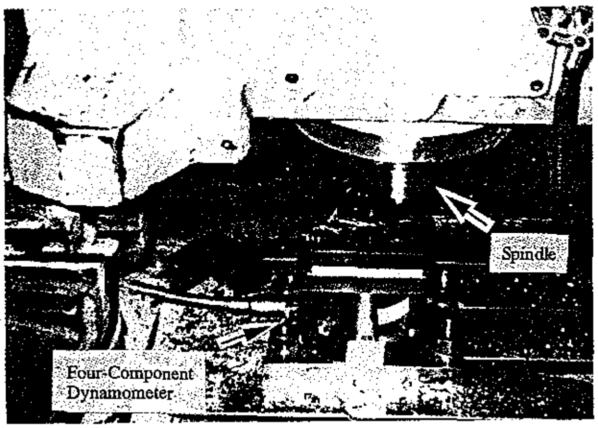


FIG.1 FOUR COMPONENT DYNAMOMETER

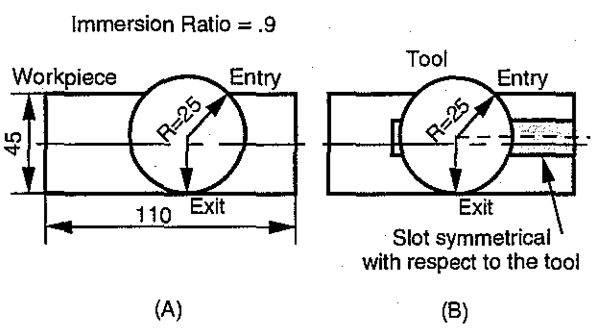
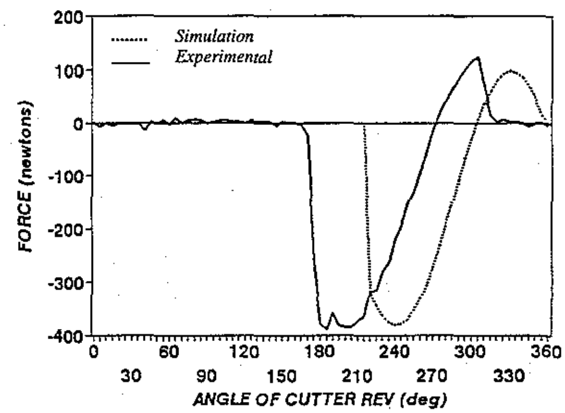
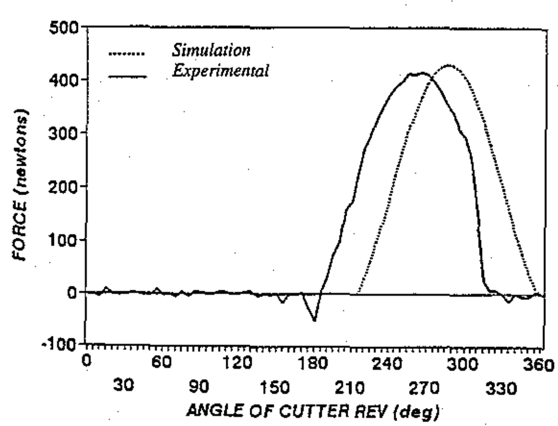


FIG. 2(A) LOCATION OF CUTTER TO WORKPIECE, AND (B) TO SLOT



(A) X-FORCE



(B) Y-FORCE

FIG. 3 COMPARISON OF EXPERIMENTAL AND SIMULATION FORCE (FLYCUTTING-CONDITION 8)

was directly determined by the immersion ratio employed. Immersion was maintained at 90% with the slot positioned in the workpiece so that the cutter and slot centre were collinear. This ensured symmetrical variation of exit-entry angle pairs with cutter progression over the workpiece and thereby simplified the analysis procedure (Fig. 2b)

COMPARISON WITH SIMULATION

A series of simulation was carried out based on the mechanistic model (Fu, et al. (1984)). The simulation results were compared with their experimental counterparts. The results from the flycutting tests were used to establish the value of the empirical constants K_t and K_r required by the mechanistic simulation model and the established values are listed in Table 2. Comparisons between the experimental and simulated versions for flycutting indicate a very close correlation and concurrence in shape and magnitude (Fig. 3).

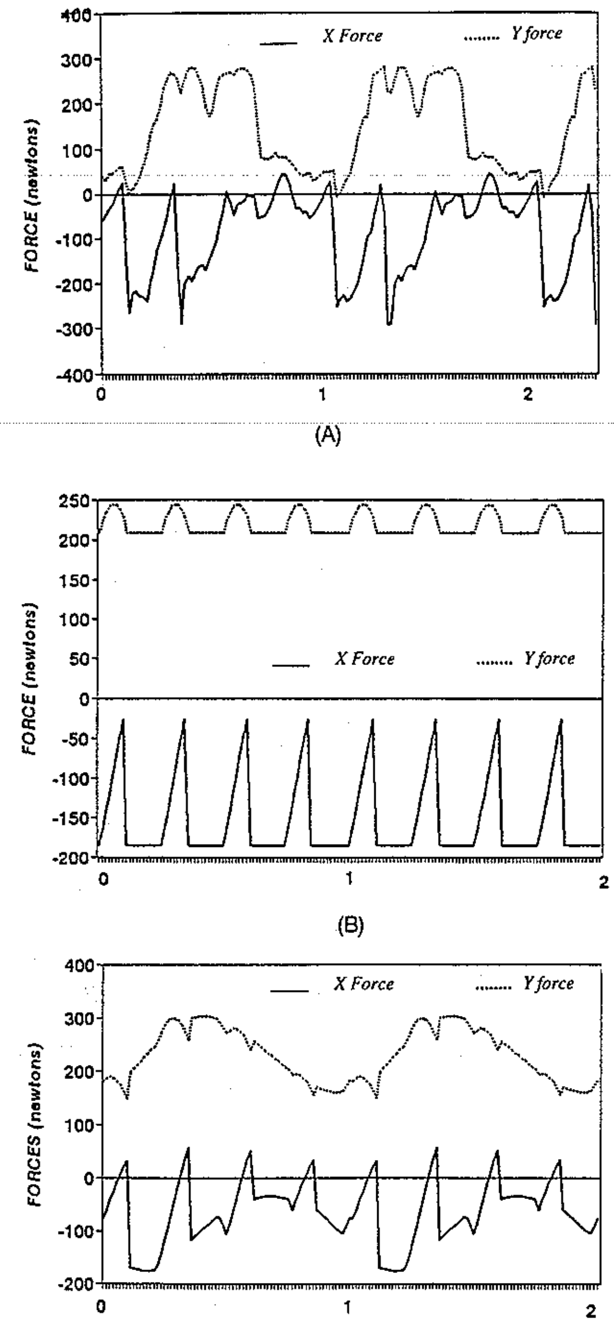


FIG. 4 (A) EXPERIMENTAL, (B) SIMULATION WITHOUT RUNOUT, AND (C) SIMULATION WITH RUNOUT (FU, et al. 1984) FORCE FOR CONDITION 7

As far as multi-tooth cutting is concerned, it was confirmed that, among other factors, knowledge about runout plays a significant role in obtaining realistic simulation results. Fig. 4 compare the experimental and simulated profiles for the case of no runout as well as runout. The significant improvement in simulated prediction as a result of inputting runout estimates into the mechanistic model is clearly discernible and indicates that the strategy of estimating runout (Fu, et al. (1984)) can provide reasonable results. But further improvement may be desirable. It is

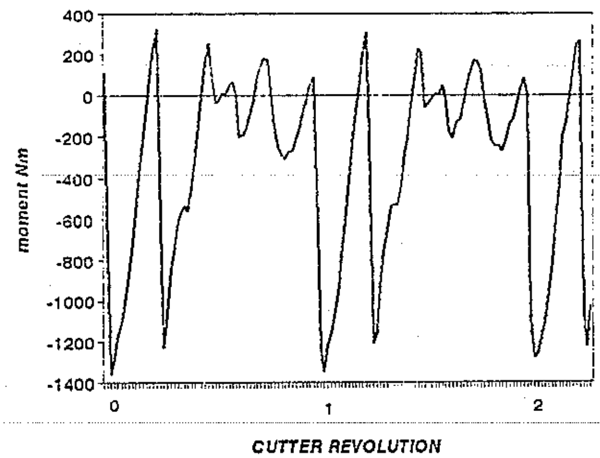


FIG. 5 MOMENT MEASUREMENT CHANGES MORE DRAMATICALLY WITH RUNOUT THAN FORCE MEASUREMENT DOES IN FIG. 4(A) CONDITION 7

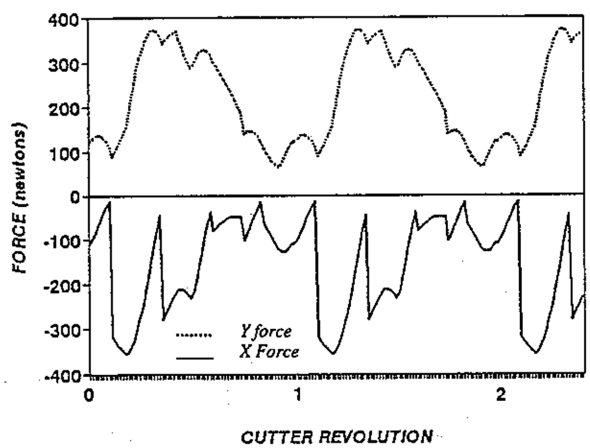


FIG. 6 SIMULATION FORCE BASED ON RUNOUT ESTIMATED USING TORQUE SIGNAL CONDITION 7

shown below that the moment measurement enables better estimation of runout than the force measurement because the former is more sensitive to runout.

IMPROVED ESTIMATION OF RUNOUT USING TORQUE MEASUREMENT

In multi-tooth face milling, each insert may have a radial throw (a type of runout) that is totally independent and unrelated to the other. As such, prediction is much more difficult. Since the force is only linearly related to the instantaneous chip load and thus runout, it may be not sensitive enough to runout. It is perceived that the torque measurement may be more sensitive to such runout because the torque is a product of force and effective cutting radius, both depends on runout. It was confirmed experimentally. As seen in Fig. 5, the moment measurement changes with runout more dramatically than the force measurement does (Fig. 4a). So, an estimation procedure, largely based on the procedure outlined in (Fu, et al. (1984)) except using torque instead of force measurement, was used to estimate runout. The estimated runout is then applied to the mechanistic model and a closer agreement of experimental and simulation results seems evident (Fig. 6). The procedure is outlined in the appendix.

FEEDRATE PROFILE DESIGN

The design of a variable feedrate profile provides a way of increasing productivity of milling of workpieces with variable radial geometry. Of particular relevance to this paper was the fact that the workpieces in specific situations (as in reworking) involve milling over existing slots and holes or cavities of geometry that are combinations of these. The maintenance of a constant average force during cutting of such workpieces provides that standard on which we can base manipulation of the feed. By maintaining constant average force during the cut, we compensate for the period of no cutting (over the slot or hole) by increasing the cutting action over the rest of the revolution.

Practical applications of the feedrate profile would primarily be in production environments incorporating large batch sizes, where relatively small increases in productivity per workpiece would contribute in total to substantial gains in process productivity overall.

Comparison of Experimental and Simulated Instantaneous Force

In considering the force regime when milling over workpieces with variable radial depth as in the case of slots and holes, it is necessary to accommodate for the change in radial depth and change in entry and exit angles (pairs) as the cutter progresses over the slot or hole. These angles change in a different way depending on whether the cutter is milling over a slot or a hole.

Milling over slots involves three stages, once the cutter has entered the slot: i) transient entry cut, ii) steady state, and iii) transient exit cut. Entry and exit angle behaviour over these types of cuts dictates the way average force falls or increases.

In the entry section of the slot, which this paper is focused on, the average resultant force drops in a non - linear fashion as the entry angle changes per revolution of the cutter. Once the cutter traverses the top and bottom hand corners of the slot the average resultant force reaches a constant level.

Eight tests were implemented under the conditions outlined previously and the instantaneous and average resultant force plots obtained. The experimental and simulated results for milling over a workpiece with slot centre aligned to that of the cutter are shown in Fig. 7, respectively. The results compare favourably overall although it is obvious that the estimate of runout, based on the torque measurement discussed above, is still not precise, resulting in observable differences in shape between the two force profiles. The gaps that signify periods of non cutting are progressively increasing in size with each revolution before achieving stability in the steady state.

Average Force

Fig. 8 offers a comparison between the experimental and simulated average force for conditions 2, 6 and 8 and indicates a close affinity.

The major difference observable is that average force decline for the experimental case is slower than that predicted by the simulation. For example, for condition 6 the simulation predicts that the cutter will have reached the steady-state portion of cutting in one revolution of the cutter, whereas the experimental results indicate that the steady-state is reached after three revolutions of the cutter. For conditions 2, entry into the steady-state is predicted after two revolutions but actually occurs after four. In turn, the steady-state for condition 8 is reached after four revolutions, one more that predicted by simulation. These discrepancies are easily reconcilable in that the real-life situation is much different to the theoretical which assumes that the response of force to changes in radial depth is instantaneous. But the delay is not difficult to account for (Tlusty, and MacNeil, (1975)).

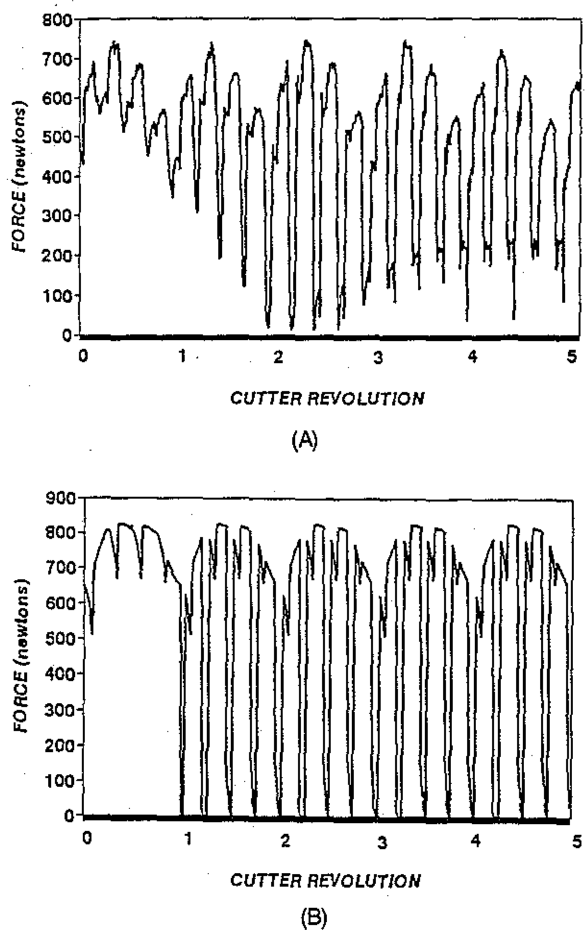
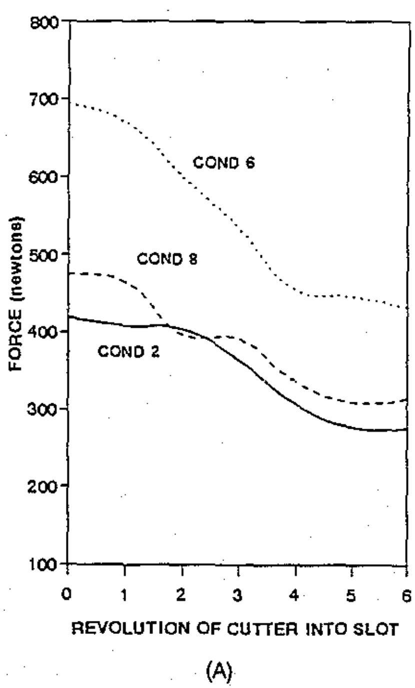
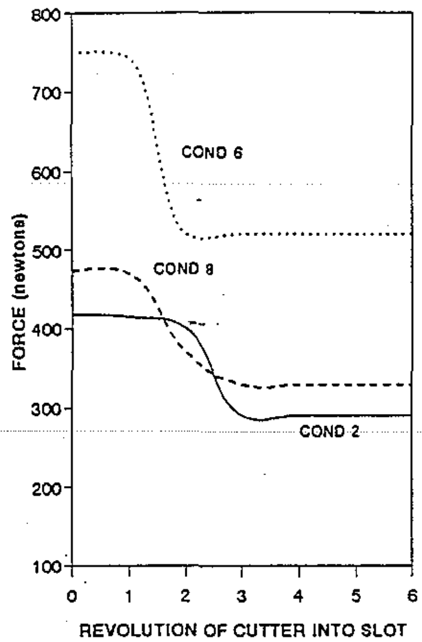


FIG. 7 (A) EXPERIMENTAL AND (B) SIMULATED INSTANTANEOUS RESULTANT FORCE FOR SLOT ENTRY (CONDITION 6)



(A)



(B)

FIG. 8 (A) EXPERIMENTAL AND (B) SIMULATED AVERAGE RESULTANT FORCE FOR SLOT ENTRY

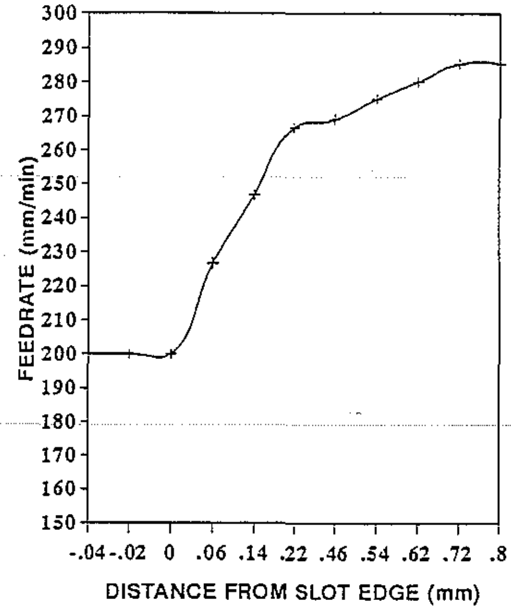


FIG. 9 GRAPHICAL REPRESENTATION OF FEEDRATE PROFILE (FRP) FOR CONDITION 3

In terms of decrease in magnitude from point of entry to steady-state cutting, the experimental and simulated outcomes are extremely good and are summarised in Table 3. Thus, overall the simulated values agree reasonably with the experimental results.

Variable Feedrate

The use of inverse solutions to engineering problems is not a new concept. In the field of milling a very recent work is that of Altintas and Spence (1992) who use an inverse procedure to design a solid modeller based milling process simulation and planning system. In their work they use pre-stored intersection data from a Constructive Solid Geometry based simulation system in combination with an analytic redefined mechanistic milling model to simulate the milling of specific parts. An inverse solution of the milling model is then used to adjust feedrate for solution of predefined constraints on force, moment and part tolerances.

In designing a variable feedrate profile for the milling process when cutting over work pieces of variable radial depth, a similar concept to that employed by Altintas and Spence can be utilised which makes use of the mechanistic model as a basis for solution.

It can be shown that, given tool geometry, instantaneous cutting force expressed in terms of its x and y components can be written as

$$F_x(\phi) = \left[\sum_{i=1}^{N_t} \delta(\theta_i(\phi))\, A(\theta_i(\phi))\right] f_t = U(\phi)\, f_t \tag{1}$$

$$F_y(\phi) = \left[\sum_{i=1}^{N_t} \delta(\theta_i(\phi))\, B(\theta_i(\phi))\right] f_t = V(\phi)\, f_t \tag{2}$$

where ϕ is angle of cutter rotation , θ tooth location, $\delta(\theta_i(\phi)$ Dirac Delta function, f_t feedrate in mm per tooth, and N_t number of inserts. Given tool geometry, $A(\theta_i(\phi))$ and $B(\theta_i(\phi))$ are constant for a specific angle of cutter rotation. The rather involved expressions inside the brackets are functions of instantaneous cutter rotation ϕ which are readily obtainable. Therefore, the forces are linear functions of feedrate f_t only and so is the instantaneous resultant force

$$R = \sqrt{F_x{}^2 + F_y{}^2} = \sqrt{U^2+V^2}\, f_t \tag{3}$$

The average force over a revolution is then equal to

$$\bar{R} = \frac{\sum_{i=1}^{n} R}{n} \tag{4}$$

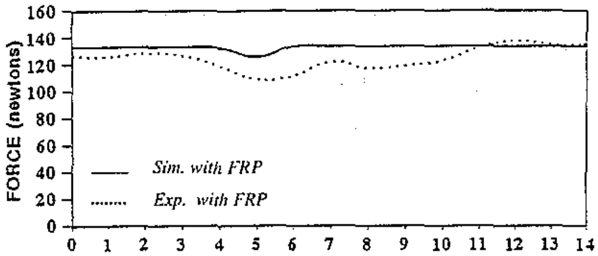
where n = the number of observations within a revolution. As seen, the average force over a revolution is a linear function of the feed alone, with all other parameters having known values at some angle of cutter rotation ϕ, or tooth location θ. Therefore, determining a proper feedrate profile such that average resultant force is kept constant is a simple matter of solving for the feed using Eqs. 1 to 4.

Case Study

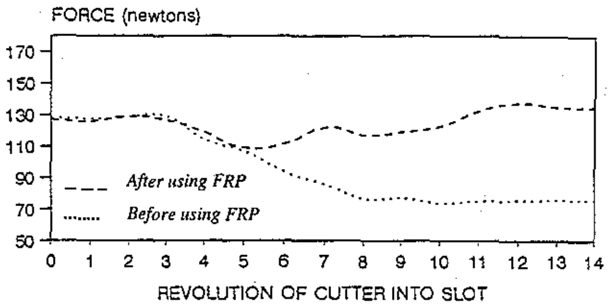
Experimental validation of the profile algorithm was undertaken for condition 3. Shown in Fig. 9 is the feedrate profile determined to achieve a constant average force when the cutter is entering the slot.

The aim of designing a feedrate profile for milling over slots and holes was to maintain a constant average force over the milling cut as a whole. Fig. 10a offers a comparison between simulated and experimental force behaviour for condition 3 with feedrate profile deployment. The correlation between the two plots is very good and indicates that the algorithm was successful in maintaining a constant average force for the duration of sampling time.

Fig. 10b compares the average force behaviour for the case without application of feedrate profile and the case with application of feedrate profile. The difference is quite distinct - an



(A)



(B)

FIG. 10 (A) COMPARISON OF SIMULATED AND OBSERVED AVERAGE FORCE USING THE FEEDRATE PROFILE (FRP) DEPICTED IN FIG. 9, AND (B) COMPARISON OF EXPERIMENTAL AVERAGE FORCE BEHAVIOUR BEFORE AND AFTER FRP FOR CONDITION 3

almost constant level of average resultant force is apparent for the case where feedrate profile implementation has been undertaken.

Indeed, the observed average resultant force in the steady-state is a little higher than that at the entry point and compensates for the fall in average force on entry into the slot. This fall moreover, is predicted in the simulated version as well although shown to last for less time than it actually does. The difference though is only small and quite acceptable in light of the stochastic nature of experimentation. Overall, the variable feedrate profile algorithm was verified in experimentation and can easily be applied to other conditions for slots as well as for holes.

CONCLUDING REMARKS

A variable feedrate profile algorithm was developed to accommodate for decreases in productivity arising from the milling of workpieces with variable radial depth. Emphasis was placed on analysing face milling of workpieces with slots and holes due to their prevalence in components used in industry.

Adoption of a suitable and comprehensive mechanistic model allowed accurate prediction of instantaneous forces to be made with the aid of computer simulation. In addition, a runout estimation procedure based on torque measurement provides improved runout values which is significant in estimating the instantaneous force. However, the effect of runout in regards to average force was found to be negligible and was not a factor in the ultimate form of the variable feedrate profile developed.

The feedrate profile algorithm developed was based on using an inverse solution to the milling expressions in the mechanistic model so that the feed rate automatically adjusted to keep the average resultant force constant throughout the total milling cycle.

Experimental testing of the feedrate profile design in the case of a workpiece with a slot was very successful, with predicted and experimental results concurring favourably.

APPENDIX

Instantaneous moment in face milling can be expressed as

$$M_T(\phi) = \sum_{i=1}^{N_t} \delta(\theta_i(\phi))\, F_T(i, \theta)\, R_E(i) \qquad (5)$$

where $F_T(i, \theta)$ is instantaneous tangential force and $R_E(i)$ effective cutting radius for insert i. Eq. 5 can be further expressed as

$$M_T(\phi) = \sum_{i=1}^{N_t} \delta(\theta_i(\phi))\, K_T\, C_l(\theta_i(\phi))\, d\, (R+\varepsilon(i)) \qquad (6)$$

$$= \sum_{i=1}^{N_t} \delta(\theta_i(\phi))\, K_T\, (f_t \sin\theta_i(\phi)+\varepsilon(i)-\varepsilon(i-1))\, d\, (R+\varepsilon(i)) \qquad (7)$$

where K_T is specific cutting pressure, $C_l(\theta_i(\phi))$ chip load, d axial depth of cut, R nominal cutter radius, and $\varepsilon(i)$ radial throw of tooth i.

Given ϕ, $M_T(\phi)$ can be measured thus Eq. 7 is only a function of *up* to N_T unknown radial throws $\varepsilon(i)$, for i = 1,2, ... N_T, depending on the cutting geometry concerned. For the multi-tooth experiments reported in this paper (4 inserts and immersion ratio of 90%), Eq. 7 was a function of two or three radial throws depending on whether one or two inserts are engaged in cutting.

But for any cases, Eq. 7 gives a second order algebraic equation of $\varepsilon(i)$s. All $\varepsilon(i)$s can be numerically determined by taking up to N_T measurements of torque, substituting them into Eq.7, and then solving the N_T equations simultaneously. The numerical method used in this work is Newton-Raphson method.

TABLE 3 COMPARISON OF AVERAGE FORCE DECREASE FROM ENTRY POINT TO STEADY-STATE (SLOTS)

Exp. No.	Experimental	Simulation	Difference
2	30%	29%	+ 1%
6	34%	31%	+ 3%
8	31%	28%	+ 3%

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