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Invited paper

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VERIFICATION OF A PROCEDURE FOR FEEDRATE SCHEDULING FOR CONSTANT FORCE IN 2D MILLING OPERATIONS

Abstract: *This paper presents a brief overview of the developed procedure for off-line optimization of CNC program. The procedure refers to milling operations in plane z=const, using flat end mills. The goal of optimization is to create modified version of part program, using feedrate scheduling, in order to keep desired milling force component on predefined value along tool path. Detailed experimental verification of this procedure is carried out using a representative example and machining test.*

Key words: *CNC milling, milling forces, optimization, federate scheduling*

1. INTRODUCTION

Nowadays many research activities in the field of CNC machining are clustered in a concept of Virtual machining (VM) [1]. Besides function of realistic predictions of outputs of machining process through simulation, extremely important function of VM is its ability to perform off-line optimization of designed process. Optimization criteria are different: keeping constant cutting force, maximization of material removal rate, limitation of machining errors, chatter-free machining, etc. The function of CNC program re-planning in order to keep cutting force level constant along tool path is partly implemented in modern CAM software [2,3]. Very impressive results were achieved through re-planning of tool path shape (trochoidal paths and morphing spiral paths in pocket machining) in the software. Such paths assume constant tool/workpiece immersion on the whole path. Another way to keep cutting force constant assumes re-planning of feedrates along programmed path. In CAM systems it is achieved through keeping constant material removal rate. A number of published research results use more precise and more demanding approaches which include milling force prediction based on generated simulation model.

2. PROCEDURE FOR FEEDRATE OPTIMIZATION

Simplified description of the procedure for off-line feedrate optimization is shown in Fig. 1. Such optimization procedure for milling operations in plane (z=const), with flat end mills, with helical flutes and arbitrary shape of stock material was developed [4].

Term *adaptation* refers to obtaining the feedrate value which can guarantee keeping the desired level of arbitrary milling force component in specific point of programmed tool path, with predefined workpiece material, cutter geometry, and configuration of tool engagement (engagement map) in the point. Procedure for feedrate adaptation has to be conducted in each point of uniformly discretized tool path. Next step is feedrate *optimization* along tool path. In this step, adapted values are subject to modifications, according to several additional criteria and re-discretization of tool path with constant feedrate on each path segment described by one block of optimized part program.

For arbitrary set of cutting parameters and engagement map, instant and representative values of milling force components can be identified. Instant values of one force component assume its periodic variation during one spindle revolution. Representative value of this component can be obtained by extraction of min/max/mean values from instant values. Important building block of optimization procedure is a module for reliable milling force prediction, as a part of step K2 (Fig. 1).

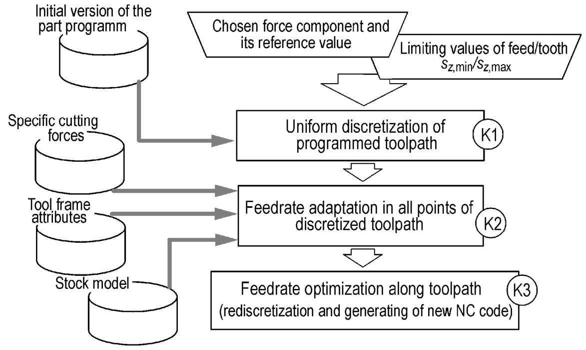


Fig. 1. Basic steps in procedure for feedrate optimization

Many authors [5,6] use procedure for feedrate adaptation which has two steps. In the first step, adaptation process for a given point on the tool path assumes calculation of feedrate based on reference force level F_{ref}, and predicted force value $F_{p(0)}$ for initially programmed feedrate $v_{s,0}$:

$$v_s^{Ad} = v_s^{Ad(1)} = v_{s,0}\frac{F_{\text{ref}}}{F_{p(0)}} \tag{1}$$

This feedrate and spindle speed n_{GV} result in a feed/tooth value as input for new simulation of instant force values (1 turn of cutter) for predicting appropriate representative force value $F_{p(1)}$ of a chosen force component. Then, it is possible to obtain adapted value of feedrate in the second step:

$$v_s^{Ad} = v_s^{Ad(2)} = v_s^{Ad(1)} + \frac{(v_s^{Ad(1)} - v_{s,0})(F_{\text{ref}} - F_{(0)})}{F_{\text{p(1)}} - F_{(0)}} \tag{2}$$

3. AN EXAMPLE OF OFF-LINE FEEDRATE OPTIMIZATION IN END MILLING OF PLANAR CONTOUR

For illustration of functionality of the developed program modules for off-line feedrate optimization, an example of down milling of planar contour is presented in this section. Pre-machined stock and machined part are presented in Fig. 2.

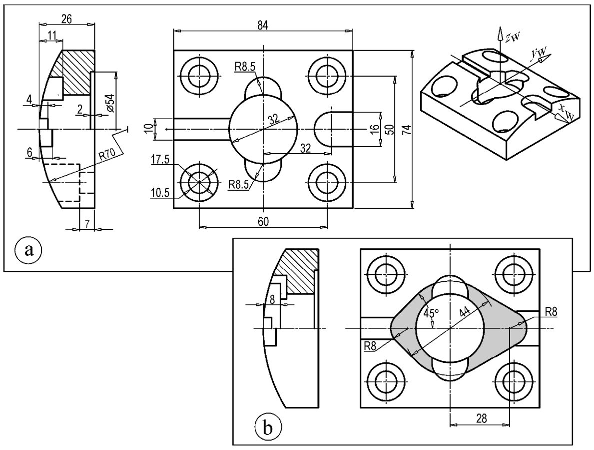
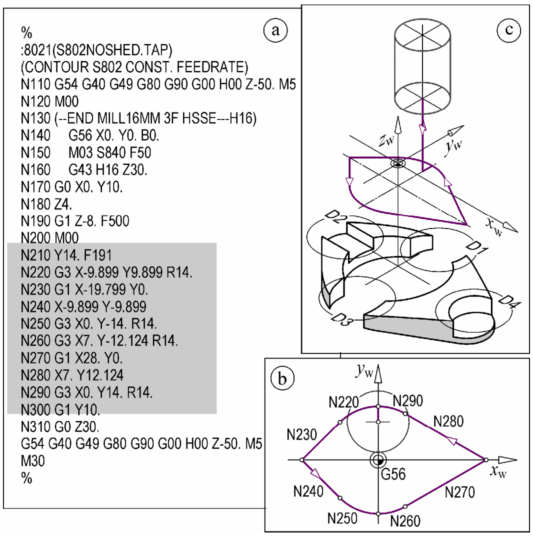


Fig. 2. Dimensions of stock (a) and machined part (b) in representative example

Workpiece coordinate system, contour shape and initial version (with constant feedrate) of the part program are shown in Fig. 3.



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%
:8021(S802NOSHED.TAP)
(CONTOUR S802 CONST. FEEDRATE)
N110 G54 G40 G49 G80 G90 G00 H00 Z-50. M5
N120 M00
N130 (--END MILL16MM 3F HSSE---H16)
N140    G56 X0. Y0. B0.
N150    M03 S840 F50
N160    G43 H16 Z30.
N170 G0 X0. Y10.
N180 Z4.
N190 G1 Z-8. F500
N200 M00
N210 Y14. F191
N220 G3 X-9.899 Y9.899 R14.
N230 G1 X-19.799 Y0.
N240 X-9.899 Y-9.899
N250 G3 X0. Y-14. R14.
N260 G3 X7. Y-12.124 R14.
N270 G1 X28. Y0.
N280 X7. Y12.124
N290 G3 X0. Y14. R14.
N300 G1 Y10.
N310 G0 Z30.
G54 G40 G49 G80 G90 G00 H00 Z-50. M5
M30
%
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Fig. 3. Example of the feedrate optimization procedure checking: part program (a), tool path (b), and material volume which will be removed (c)

Workpiece material was AlZn4Mg2 (ENAW 7019) with R_m=390MPa and hardness of 125HB. Tool was DIN327 end mill, HSSE (8%Co) with 3 teeth, D=16mm, helix angle 30° and rake angle 11°. Clamping of tool: ISO40/OZ52∅16 collet. Measured runout parameters of the cutter: ρ_0=0.01mm, φ_0=81°. Experimentally identified specific cutting forces [4] for given workpiece material and cutting geometry were:

$[K_{tc}\ K_{rc}]$ = [1113.0 384.2] N/mm^2,

$[K_{te}\ K_{re}]$ = [11.1 11.6] N/mm.

Keeping constant value of the resulting milling force in xy plane - F_{xy} on the level of 800N, along the tool path, was chosen as optimization criterion.

Form of the stock and shape of the tool path were chosen to ensure rapid changes in cutting depth as well as cutting width along the tool path. Cutting parameters, used in initial version of part program (before feedrate optimization) are shown in Table 1.

a [mm]	n_S [min^{-1}]	$v_{f(0)}$ $^{1)}$ [mm/min]	b [mm]	$s_{t,0}$ $^{1)}$ [mm/t]
min. 0 max. 8	796	191	min. 0 max.16	0.08

$^{1)}$ Programmed in initaial version of part programm

Table 1. Parameters of machining test

3.1. Feedrate adaptation

According to flow chart in Fig.1, it was necessary to prepare stock model. This preparation assumes building its Z-map model. Such map, made from STL-file (exported from CAD program) of the stock is shown in Fig.4. Values of other parameters of the procedure for feedrate adaptation are shown in Table 2.

Toolpath discretization increment ΔL_p [mm]	0.5
Increment of the Z-map base Δm[mm]	0.5
Disc thickness of discretized tool h_d [mm]	0.5
Increment for one turn simulation $\Delta\theta$ [°]	1.0
Reference force value, F_{ref} [N]	800
Feed limits $s_{z,min}$, $s_{z,max}$ [mm/t]	[0.03, 0.25]

Table 2. Parameters of the procedure for adaptation of the feedrate in points of dicretized tool path

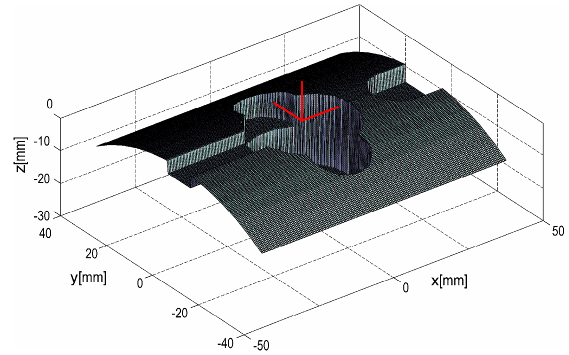

Fig. 4. Z-map of the stock for given example

Totally 250 points were obtained on tool path through its uniform discretization with given increment ΔL_p. Each of these points was a subject of feerdate adaptation (1,2). This procedure assumes calculation of appropriate feedrate which will keep milling force F_{xy} on F_{ref} level, respecting lower $s_{z,min}$ and upper level $s_{z,max}$ of feed per tooth (Tab.2) and specific cutting conditions in this point.

Some details of this procedure for one point are shown in Fig.5: obtaining tool engagement map (using updated workpiece Z-map, tool attributes, instant direction of feedrate vector and position of point), obtaining enter/exit angles for each tool disc in engagement map, and prediction of instant values of milling forces through simulation in single turn of the tool. This simulation has to be carried out two times: for initial feedrate and for feedrate per tooth $s_z^{(Ad1)}$ obtained from (1). It is enough to find required value for $s_z^{(Ad2)}$ (2). Lower diagram in Fig.5 shows predicted instant values of milling force components for $s_{z,0}$, $s_z^{(Ad1)}$ and finally for $s_z^{(Ad2)}$. Fig 6. shows adapted values of feedrate in all points of discretized tool path, as well as predicted values of representative force, before and after adaptation.

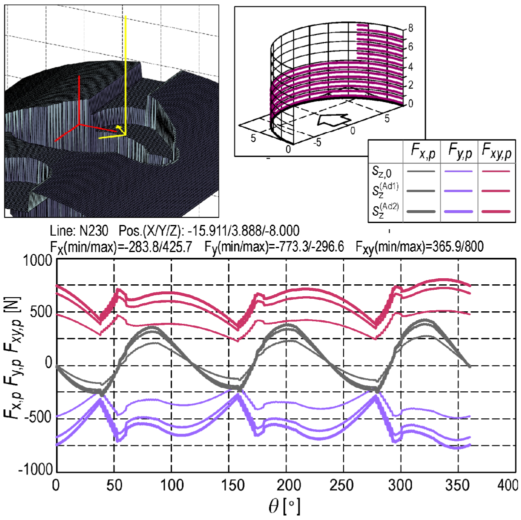

Fig.5. An example of feedrate adaptation in specific point of the tool path

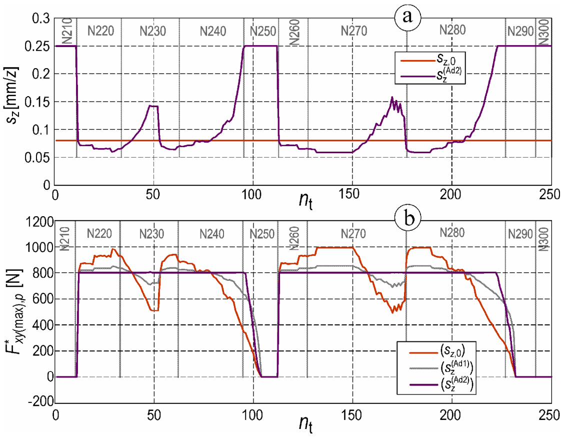

Fig.6. Programmed feedrate and feedrate after adaptation (a) and predicted representative force values (b) for programmed (constant) feedrate and with adapted feedrates

3.2. Feedrate optimization along tool path

Optimization of feedrate along tool path starts from calculated values obtained through adaptation process in points of uniformly discretized path. Keeping such discretization can lead to forming enormously long code of part program and undesirably frequent variation of feeedrate on short path segments (high acceleration/decceleration and unstable operation). In this sense, optimization should have the following steps:

S1. Filtration of feedrate values obtained in process of its adaptation
S2. Rounding of adapted values of feedrate on discrete values of scale with previously chosen increment and aggregating subsequent path segments (uniform discretization) of the same block of initial program into longer segments with one value of the feedrate (the first step of re-discretization)
S3. Second step of re-discretization with modified values obtained in S2 in order to guarantee limited accel/decelerations of machine servo axis.

Through the procedure of feedrate adaptation, regarding initial description of tool path (program of Fig.3a) and according to given parameters (Tab.2) the re-discretization of tool path is carried out. According to steps S1-S3 this re-discretization reduced number of tool path segments from 250 (uniform discretization) to 55. These segments with assigned feedrates are shown in optimized version of the part program (Fig.7) in blocks from N200 to N740.

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%
:8022(S802RESSHED.TAP)
(SHEDULING FXY 800N )
(RESHED. VSINCR=30MM/MIN)
G54 G40 G49 G90 G0 H00 Z0. M5
M00
N130 (-- 16MM 3F HSSE---H16)
N140 G56 X0. Y0. B0.
N150 M03 S796 F191
N160 G43 H16 Z30.
N170 G0 X0. Y10.
N180 G1 Z-8. F200
N190 M00
N200 G1 X0. Y14.000 F570
N210 G3 X-0.500 Y13.991 R14. F360
N220 G3 X-0.999 Y13.9643 R14. F180
N230 G3 X-7.987 Y11.4979 R14. F150
N240 G3 X-9.543 Y10.2436 R14. F120
N250 G3 X-9.899 Y9.8990 R14. F150
N260 G1 X-11.313 Y8.485 F150
N270 G1 X-12.374 Y7.424 F180
N280 G1 X-13.435 Y6.364 F210
N290 G1 X-13.788 Y6.010 F240
N300 G1 X-14.495 Y5.303 F270
N310 G1 X-15.203 Y4.596 F300
N320 G1 X-16.617 Y3.182 F330
N330 G1 X-16.970 Y2.828 F180
N340 G1 X -19.799 Y0. F150
N350 G1 X-16.970 Y-2.828 F150
N360 G1 X-13.081 Y-6.717 F180
N370 G1 X-12.020 Y-7.778 F210
N380 G1 X-10.960 Y-8.838 F240
N390 G1 X-9.899 Y-9.899 F270
N400 G3 X-9.540 Y-10.247 R14. F330
N410 G3 X-9.168 Y-10.581 R14. F390
N420 G3 X-8.784 Y-10.901 R14. F420
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N430 G3 X-8.389 Y-11.208 R14. F480
N440 G3 X0. Y-14.000 R14. F570
N450 G3 X 0.500 Y-13.991 R14. F180
N460 G3 X7.000 Y-12.124 R14. F150
N470 G1 X8.7321 Y-11.124 F150
N480 G1 X17.392 Y-6.124 F120
N490 G1 X19.558 Y-4.874 F150
N500 G1 X20.424 Y-4.374 F180
N510 G1 X21.723 Y-3.624 F210
N520 G1 X23.022 Y-2.874 F240
N530 G1 X24.321 Y-2.124 F270
N540 G1 X24.754 Y-1.874 F300
N550 G1 X25.620 Y-1.374 F330
N560 G1 X27.676 Y-0.187 F300
N570 G1 X28.000 Y0. F270
N580 G1 X22.804 Y3.000 F120
N590 G1 X19.340 Y5.000 F150
N600 G1 X14.143 Y8.000 F180
N610 G1 X13.277 Y8.500 F210
N620 G1 X12.844 Y8.750 F240
N630 G1 X11.978 Y9.250 F270
N640 G1 X11.545 Y9.500 F300
N650 G1 X11.112 Y9.750 F330
N660 G1 X10.679 Y10.000 F360
N670 G1 X10.246 Y10.250 F390
N680 G1 X 9.813 Y10.500 F420
N690 G1 X 9.380 Y10.750 F450
N700 G1 X8.947 Y11.000 F510
N710 G1 X8.514 Y11.250 F540
N720 G1 X7.000 Y12.124 F570
N730 G3 X0. Y14.000 R14. F570
N740 G1 X0. Y10.000 F570
N750 G0 Z30.
G54 G40 G49 G90 G0 H00 Z0. M5
M30
%
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Fig.7. Part program after optimization of feedrates along tool path

4. MACHINING TEST

Quality of the described procedure for off-line feedrate optimization was proven through machining test that was carried on the horizontal machining center (HMC500/40, Lola Corp.). Components of experimental setup were: four component dynamometer with strain gauges (DYN3F1M-M83, KaProM), two displacement sensors (W50, HBM), 4 amplifiers (KWS3082A, HBM), DAQ system (cDAQ9174 + 9215 Voltage module, NI) and computer with software for DAQ (LabView, NI). Workpiece was clamped on the platform of the dynamometer (Fig. 8)

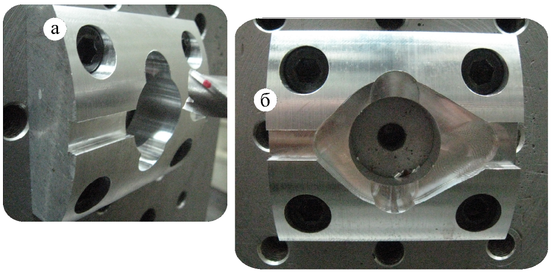

Fig.8. Stock (a), and machined contour (b), in machining test

Experimental setup allows acquisition of two signals from dynamometer (force components along x_w and y_w axes), as well as two signals of actual positions x_w and y_w of machine servo axis. These four signals are enough for reconstruction of changes of resulting milling force F_{xy}, along tool path. Fig.9 shows measured instant values of one force component ($F_{x.w}$) during machining of the contour, according to part program from Fig.7. During experiment a chatter vibrations occurred on some segments of the tool path. It is shown in details (W1 and W2) in Fig.9.

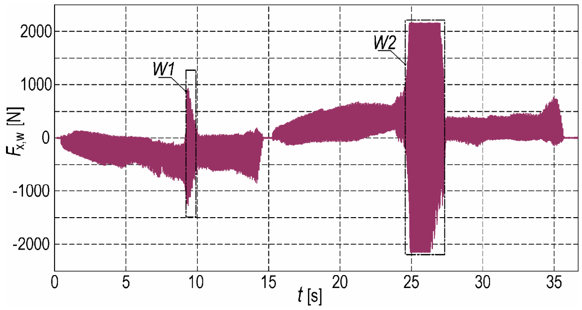

Fig. 9. Instant values of $F_{x.w}$ milling force component (signal from dynamometer) during machining of the contour

Measured positions of machine servo axis (x_w, y_w) during machining test in given example are shown in Fig.10.

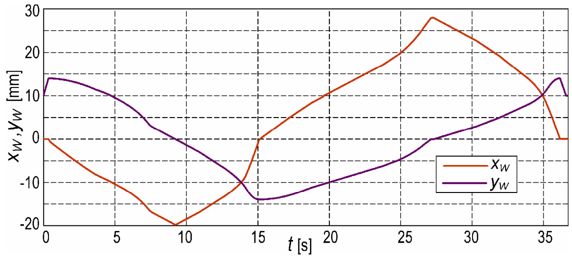

Fig. 10. Measured positions of machine servo axis (x_w, y_w) during machining of the contour

All four signals were collected simultaneously during experiment and allow generation of diagram with distribution of representative cutting force along the tool path. Such diagram is shown in Fig.11. Instant values of milling force, in sample k, were obtained as:

$$F_{xy}(k)=F_{xy,\mathrm{w}}(k)=\sqrt{F^2_{x,\mathrm{w}}(k)+F^2_{y,\mathrm{w}}(k)} \tag{3}$$

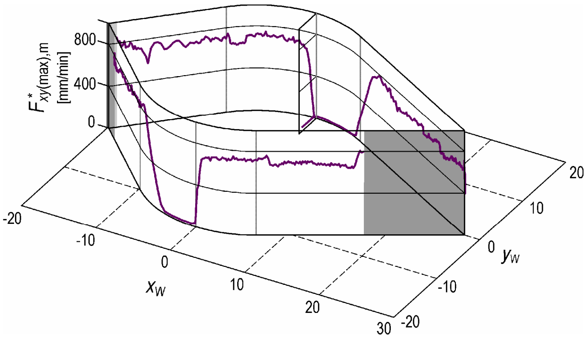

Fig. 11 . Distribution of $F^{*}_{\mathrm{xy(max),m}}$ milling force along tool path, obtained from experiment

Representative values of milling force, extracted for every spindle revolution were obtained as:

$$F^{*}_{xy(\max),m}(q)=\max\{F_{xy,\mathrm{w}}(k)\}$$
$$k=(q-1)\cdot n_s \div q\cdot n_s,\ \ q=1,2,... \tag{4}$$

Integer n_s denotes the number of samples that refer to one spindle revolution. These values are assigned to points on tool path with coordinates:

$$x_w(q)=x_w(k),\ \ y_w(q)=y_w(k),\ \ k=q\cdot n_s \tag{5}$$

Diagram in Fig.11 is broken into two too lpath segments. These segments are shaded and they refer to chattering which is not included in developed model for milling force prediction.

5. CONCLUSION

This paper presents an example of experimental verification of developed procedure for off line optimization of NC program for a class of milling operations. This optimization is based on feedrate scheduling for keeping the constant milling force level. Good quality of the procedure was shown through machining test. In the trade-off between efficacy and performances of the proposed procedure, arguments are on the latter. Lower efficacy comes from the need of simulation of forces on whole turn of discretized cutter geometry in each point of uniformly discretized tool path. Improvements, in this sense, are the subject of our present research activities.

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6. REFERENCES

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