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A Study on Circular Contour Machining Error

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Abstract

The comprehensive system analysis for contour milling operation and its error has performed in this study. The obtained experimental results were from the practical points of view. In down-milling operation the contour error curve illustrates bigger thean actual workpiece radius. The contour error increased when the cutter loads increased. Through the procedural evaluation, it could ascertain the characteristics of generation mechanics in circular contour machining error, and the weight of each factors.

Key Words : Circular Contour, Up-milling, Down-milling

1. Introduction

The contour machining error generated in NC milling process is an important factor estimating the quality of manufactured goods; especially it is a measure of servo system design. However, it is very difficult to analyze the contour machining error because of the complicated correlations between the servo drive system, motion delivering elements, and cutter to workpiece cutting mechanics. For this reason, several research attempts were not very successful to determine the relationships effectively.

The problem of reducing path error or individual axis error may be achieved through path preprocessing in which a dynamic model of the machine system is utilized in the path planning process (Park(1), has given a related example).

Several other authors have examined this area, notably Tomizuka(2,3), who has attempted to minimize path errors through the achieving very close to the zero phase lags between the command and actual position of each axis.

The essence of the work described by Tomizuka is through the use of a compensating filter which attempts to cancel the dynamics of the control loop; it should be evident that this type of approach presupposes a good knowledge of plant structure and parameters. Additional problems are likely to appear with any such system due to physical constraints and nonlinearities. The previous work by Weck(4) has proposed a solution to this problem by placing a low pass filter in front of the controller.

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The solution proposed by Weck alleviates the amplifier saturation problem and in practice has been shown to lead to an improved performance in corner tracking. A rather different approach to the minimization of path error has been introduced by Koren(5,6), who sets out to minimize path errors while still allowing actual individual axis position errors. The approach requires the calculation of path errors to compensate the individual axis.

The strategy suggested by Koren requires very fast hardware to allow the cross coupling errors to be achieved in a realistic fashion. The approach taken in the study(7) was intended to allow the possibility of controlling error in real time; even in those cases where constraints such as amplifier saturation were encountered. The approach mainly derives from the architecture of control system architecture developed at the University of British Columbia(8).

In the last study(12), the contour error prediction algorithm was proposed which also considers the cutting mechanics of operations as well as the errors due to the deflection of tools. In order to verify the algorithms of last study, the experimental investigation, in this study, is compared with the simulated results of last study. Understanding of the contour error in vertical end milling applications is very important for compensation the errors to achieve more accurate parts.

2. Experimental setup and procedure

In this study, we have used structural carbon steel SM45C as a workpiece and was prepared using a lathe and small holes were made to facilitate the clamping fixture on the milling machine. In addition, machinable wax workpiece was also prepared to investigate the effects of the stiffness of the materials and loads due to cutting forces. The mechanical and chemical properties of test pieces are shown in Table 1.

The end-mills used in the experiment were both 2 and 4 fluted 16 mm diameter with 30 degrees helix angle and they are made up of high-speed steel (SKH9) material.

The strain gauge force measurement system (Lebow ETN6423) was used to measure the cutting forces where the strain gauge signal is amplified through an A/D converter to get voltage signal which is then fed into a PC to acquire the data. The sampling rate was 10 kHz.

Construction of two axis NC contouring system is shown in Figure 1.

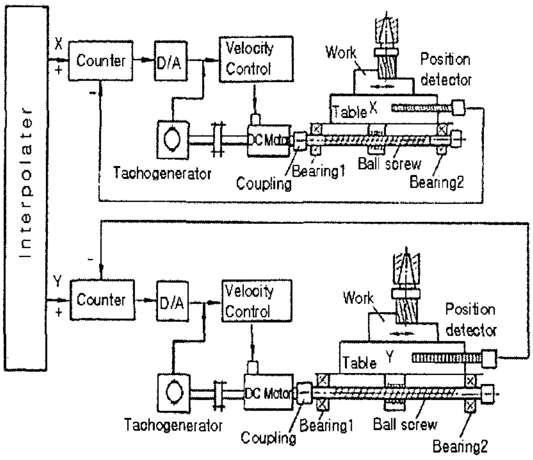


Figure1. Construction of two axis NC contouring system

Table 1 Mechanical and chemical properties of test pieces

Test Material	Mechanical Properties				
SM 45C	Hardness (HB)	Tensile Strength (kgf/mm^2)	Elongation (%)	Yield Strength (kgf/mm^2)	Reduction of area (%)
	157	71.2	18.5	36.43	31.4
	Chemical Composition (wt. %)				
	C	Si	Mn	P	S
	0.45	0.31	0.75	0.016	0.012

Table 2 Cutting conditions used in experiments

No	Group	Cutting speed (rpm)	Feed (mm/tooth)	Axial Depth of cut (mm)	Radial Depth of cut (mm)
1	Up Milling	700	0.01	20	2
2		350	0.01	20	2
3		700	0.01	20	5
4		350	0.01	20	5
1	Down Milling	700	0.01	20	2
2		350	0.01	20	2
3		700	0.01	20	5
4		350	0.01	20	5

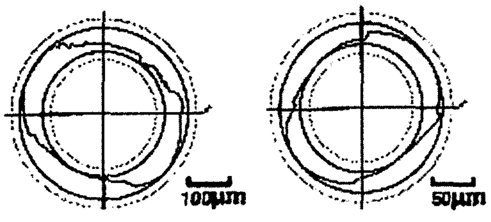
The contour error was measured by a computer measurement machine (CMM Rank Taylor Hobson RTH TR250 model) roundness tester for the machined test pieces. The accuracy of the machined surface finish measurement was approximately 0.1 mm for 3D measurements and the 5 mm diameter probe was used to measure roundness.

The experimental cutting conditions are shown in Table 2 for both up-milling and down-milling.

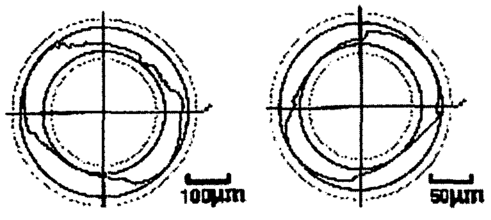
3. Results and discussion

The simulated results are compared with the experimental data for each axis of down and up milling operations for duration of one rotation of the cutter.

The roundness test results are shown in Figure 2, and Figure 3, up and down-milling, respectively. Four different cutting parameters were varied: cutting speeds at 700 rpm, and 350 rpm, as well as radial depth of cut of 2 mm and 5 mm. From the figures, circular contour error for up-milling operation shows less than the contour error



Up-Milling 1 Up-Milling 2



Up-Milling 3 Up-Milling 4

Figure 2. Circular contour machining error in the four conditions of up milling

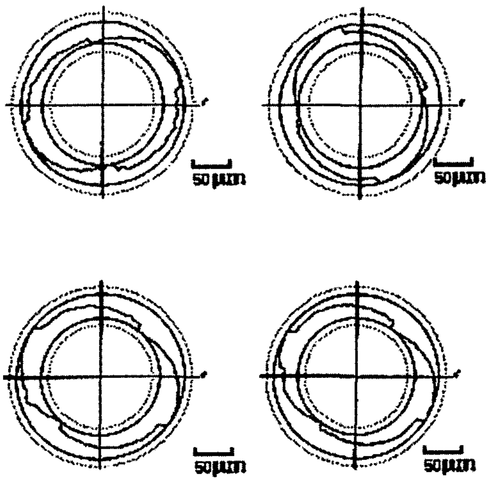
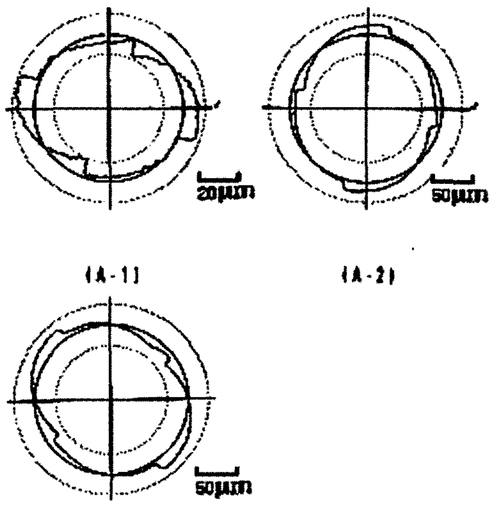


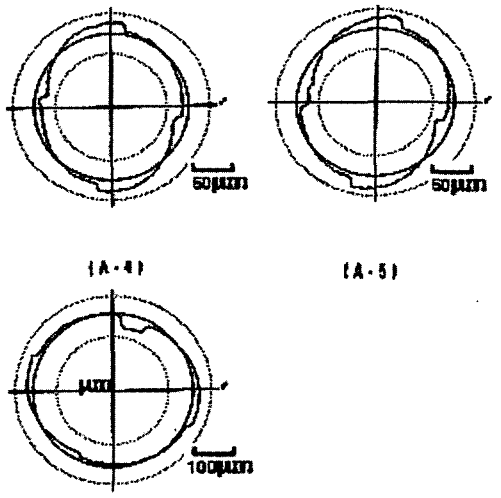
Figure 3. Circular contour machining error in the four conditions of down milling



(A-1) (A-2)

(A-3)

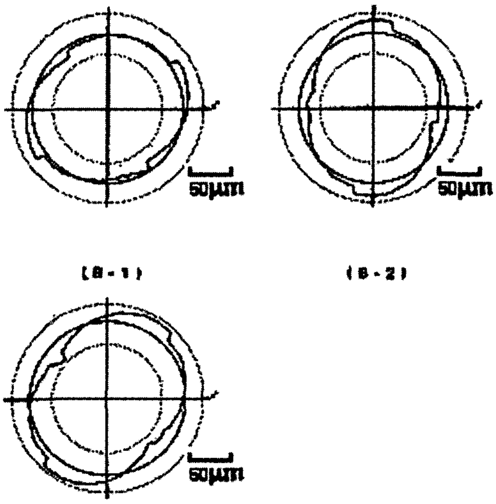
Figure 4. (a) Circular contour machining error to the variation of radial depth of cut



(A-4) (A-5)

(A-6)

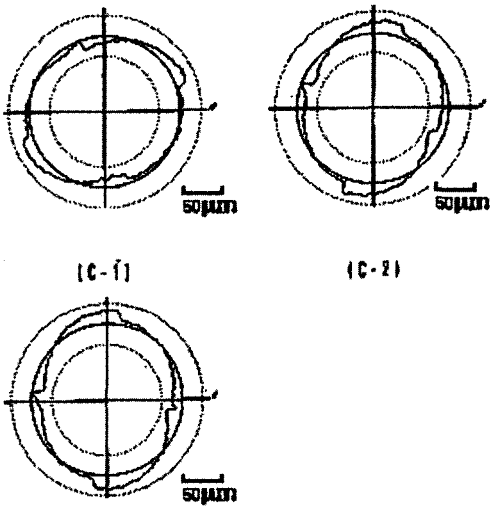
Figure 4. (b) Circular contour machining error to the variation of radial depth of cut



(B-1) (B-2)

(B-3)

Figure 5. Circular contour machining error to the variation of axial depth of cut



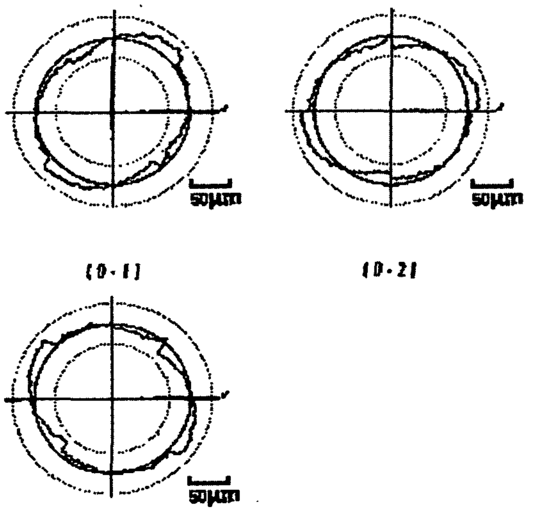
(C-1) (C-2)

(C-3)

Figure 6. Circular contour machining error to the variation of feed

in down-milling operations. The radial depth of cut and cutting speed at 700 rpm in up-milling operation shows twice the error compared with down-milling contour error.

The rate of error changes increased rapidly in up-milling compared with down-milling. The figure shows the up-milling operation cause greater servo loads compared



(D-1) (D-2)

(D-3)

Figure 7. Circular contour machining error to the variation of cutting speed

to down-milling operation. Furthermore down-milling operation at rotational speed of 700 rpm, the oscillation occurs which may be due to abrupt milling surface that cause momentary vibration due to the entrance impact.

Circular contour machining errors due to the variation of radial depth of cut is shown in Figure 4. As the radial depth of cut increases, the contour error increases. In the case of Figure 4 (A-1), even though the radial depth of cut is 1 mm, the graph shows unbalanced results. Also, as the depth of cut decreases, the results shows similar to the results from the machinable wax case this is due to decrease in servo loads and its error reduction. In addition, when the depth of cut is greater than 4 mm, the contour error results are in oval shape.

In Figure 5, the circular contour machining error to the variation of axial depth of cut is shown. As the depth of cut increases, the contour error also increases as well. In Figure 5. (B-1) where the depth of cut is 5 mm, 4 lobe contours are shown whereas Figure 5. (B-3), two lobe contours are shown.

In Figure 6, circular contour machining error to the variation of feed is shown. In this graph, as the feed increases, the contour error also increases as well. Figure 6 (C-1) exhibit less error compared with Figures (C-2) and (C-3)

In Figure 7, circular contour machining error to the variation of cutting speed, the contour error does not much affected by the cutting speed

4. Conclusion

The study investigates the experim- ental verification of contour error that is due to the servo errors as well as errors caused by dynamic behaviour of the system. The simulated results were then compared with the experimental data to come up with an effective model, which can be used to calculate the contour error in milling operations. The summary of this study follows:

In down-milling operation, the contour error curve illustrates bigger than actual workpiece radius. Whereas in up-milling operation, the contour error curve is smaller than actual workpiece radius. The contour error increased when the cutter loads increased (i.e., increasing of the radial and axial depth of cut).

Acknowledgements

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References

(1) H.A. Park. "Adaptive Matching and Preview Controllers for Feed Drive Systems". *ASME Trans. J. Engng Ind.* **113**, 316-320, 1991.

(2) M. Tomizuka. "Zero Phase Error Tracing Algorithm for Digital Control". *ASME Trans. J. Dyn. Syst. Meas. Control* **109**, 65-68, 1987.

(3) J. Buttler, B. Haack and M. Tomizuka. "Reference Input Generation for High Speed Coordinated Motion of a Two Axis System". ASME Trans. J. Dyn. Syst. Meas. Control **113**, 67-74, 1991.

(4) M. Weck and G. Ye. "Sharp Corner Tracking Using the IKF Control Strategy". *Ann. CIRP* ***39***, 437-441, 1990.

(5) Y. Koren. "Cross-coupled biaxial Computer Control for Manufacturing Systems" *ASME Trans. J. Dyn. Syst. Meas. Control* ***102***(4), 265-272, 1980.

(6) Y. Koren and C.C. Lo. "Variable Gain Cross-coupling Controller for Contourin". *Ann. CIRP* **104**, 371-374. 1991.

(7) I. Yellowley and R.J. Seethaler. "The Regulation of Position Error in Contouring Systems". *Int. J. Mach. Tools Manufact.* ***36***(6), 713-728, 1996.

(8) I. Yellowley and P.R. Pottier. "The Integration of Process and Geometry within an Open Architecture Machine Tool Controller". *Int. J. Mach. Tools Manufact.* **34**(2), 277-293, 1994.

(9) R. Ardekani and I. Yellowley. "The Control of Multiple Constraints within an Open Architecture Machine Tool Controller". *ASME Trans. J. Engng Ind.* **118**(3), 388-393, 1996.

(10) I. Yellowley and P. R. Pottier. "A Note on a Simple Method for the Improvement of Interpolation Accuracy in a General Purpose, Multiprocessor Based Motion Controller". *Int. J. Mach. Tools Manufact.* **29**(2), 287-292, 1989.

(11) L. Kops and D.T. Vo. "Determination of the Equivalent Diameter of Machinability Evaluation using a Workpiece Model". *Ann. CIRP* **39**, 93, 1990

(12) C.K.Namkoong and I. Yellowley. "Contour Machining Error in NC Milling Process". Journal of the Korea Society of Machine Tool Engineers. Vol. 10, No. 6, pp. 116～125, 2001.

(13) T.I. Seo and Y.W.Cho. "Study of Machined Surface Error Compensation for Autonomous Manufacturing System". Journal of the Korea Society of Machine Tool Engineers. Vol. 9, No. 4, pp. 75～84, 2000.