Statistical investigation of hydraulic driven circular interpolation motions

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MS received 30 October 2010; revised 3 August 2011; accepted 29 September 2011

Abstract. In this study, a twin-axis gantry has been structured to examine hydraulic driven positioning skills of the curvilinear motions based on ISO 230-4 standard entitled ‘Circular tests for numerically controlled machine tools’. The system is controlled by a path and position control module of a PLC device. As a result of the experiments conducted based on the full factorial design, the effects of piston diameter, feed rate, radius and their two-way interactions on the circularity error are determined through analysis of variance. Accordingly, minimum circularity error is obtained with the piston diameter of 63 mm, inertia load of 12.5 kg, radius of 5 mm and feed rate of 50 mm/min as 0.345 mm. Circularity error increases with the increase of inertia load, radius and feed rate, and declines with the increase of piston diameter. Lastly, piston diameter has the greatest effect on the circularity error change and followed by radius, feed rate, piston diameter–radius, radius–feed rate, piston diameter–feed-rate, inertia load, piston diameter–inertia load, and inertia load–radius factors and interactions.

Keywords. CNC; circularity error; circular interpolation motion; hydraulic positioning; ANOVA.

1. Introduction

The latest innovation point in speed and position control of machine tools in manufacturing technology is called as computer numerical control (CNC) technologies. The most important characteristics of these technologies are the machining tolerance in micron accuracy and manufacturing the sculptured geometries that can not be machined via classical machines. The closed loop control of the systems with servo motor and ball screws through measuring components

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such as encoder enable these machines work precisely. In contrast, the hydraulic systems that have the advantages of fast response speed, very high system stiffness, higher force to weight ratio and compact size lose their robustness due to nonlinear parameters such as temperature, compressibility leakages, weight and friction, which are difficult to model. Therefore, hydraulic systems are used in the sub-operations of these machines such as tail stock and tool change mechanisms.

Adaptive control and variable structure control (VSC) are the two most common approaches used to compensate for the nonlinear behaviour of hydraulic servo systems. Most of the adaptive controllers (Shih & Sheu 1991; Bobrow & Lum 1995; Hori *et al* 1989; Plummer & Vaughan 1996; Lee & Srinivasan 1990) use a linearized model for the system, and therefore provide only local stability. These systems can handle changing system parameters such as flow constants, fluid bulk modulus, and variable loading. The drawback of these linearized adaptive controllers is the lack of a global stability proof (Sohl & Bobrow 1999).

Although the classic VSC (Chern & Wu 1991; Lee & Lee 1990; Hwang & Lan 1994) is robust against external disturbances and parameter variations, it results in chattering leading to component damage and high control activity. Chattering in VSC system is divided into two types such as chattering at VSC output and the chattering of state variables in state space. These two types of chattering have different nature and are from different sources (Hung 1993). Although there are various solution methods to this problem in the literature, the continuous methods, called as varying boundary layer (Hwang 1996; Chen *et al* 2005) and reaching law (Gao & Hung 1993; Jerouane *et al* 2004; Hung & Hung 1994) approaches, focus on the chattering on the VSC output, and the switching gain method (Hwang 1996; Wang *et al* 1996; Ha *et al* 1999; Yau 2004; Hung & Chung 2007) on chattering of state variables.

The literature survey has revealed that CNC technologies are not used widely in the control of hydraulic systems but used for the positioning accuracy of linear motions investigation. Altintas & Lane (1997) carried out the single axis motion of two cylinders of press brake via open architecture CNC. Similarly, Pinar & Güllü (2010) statistically examined the positioning accuracy of the linear motion of two-axis hydraulic gantry. The optimization of the system and the effects of feed rate, motion distance, inertia load and direction parameters and their two-way interactions on the positioning error were carried out via Taguchi method. According to this, it was observed that feed rate, motion distance, feed rate-direction and motion distance-inertia load factors and interactions were significant, and the minimum positioning error was 0.089 mm. However, in this study, hydraulic driven circular interpolation motions are investigated statistically for the first time through structuring a system with a similar configuration as CNC vertical machining center.

2. Experimental set-up

The system is controlled as closed loop by 4-axis CNC controller (FM 357-2) in Siemens S7-300 PLC (Programmable Logic Controller) set. An incremental type linear encoder with 0.005 mm resolution is used as the feedback component. As seen in figure 1, the related command according to the motion to be achieved is entered as MDI (Manual Data Input) mode via the software of the controller. The parameters about the CNC command are sent to the PLC set processor via USB/MPI interface card. FM 357-2 applies the appropriate electrical signal to the proportional valve within the range of ± 10 V. The cylinders directed by the valve achieve the desired motion by moving the axis in appropriate speed. The coordinate data necessary for the measurement are collected from the parallel port of the computer. By analysing the data from X and Y axes using RapidForm 2004 commercial software, the circularity error is determined.

Figure 1. Working principle of the system.

Figure 2. Mechanical structure: (1). Y-axis cylinder, (2) X-axis cylinder, (3) Y-axis linear encoder, (4) X-axis linear encoder, (5) Y-axis proportional directional valve, (6) X-axis proportional directional valve, (7) Y-axis table, (8) X-axis table, (9) Weights.

The device consists of X and Y axes placed at 90° in a similar configuration as CNC vertical machining centre (figure 2). In the system, the movement of the axes is realized by ball rail systems (profiled rail and runner block). Mechanical structure has such a design that it is able to realize the CNC basic motions such as linear (G01) and circular interpolation (G02, G03).

2.1 CNC system

The control schema of the FM-357-2 path and position control module is given in figure 3. This control module FM357 allows the motion of maximum four axes to be controlled as a function of position. The module FM 357-2 achieves this by assigning an analogue output to each axis for the speed set point and assigning an encoder input to each axis for cyclical reading of the actual position (Siemens 2003).

In the proposed system, the proportional directional valve is used instead of servo motor. The most significant parameter of path and position control module is the K_v called as control gain. The magnitude of the K_v factor affects the following important reference variables of the axis (Siemens 2003): Positioning accuracy and holder control, uniformity of movement, positioning time.

K_v can be defined as follows

$$K_v = V / \Delta s, \quad (1)$$

where V is the velocity (m/min) and Δs the following error (mm). In the system, K_v factor is defined experimentally. In the pilot experiments, it is observed that the position accuracy decreases if the K_v value is low and chattering occurs in the cylinders if it is high. For each cylinder, a different K_v adjustment is carried out. In this way, for Ø63, Ø50 and Ø40 piston diameters of the cylinders 4, 0.4 and 0.2 K_v values are experimentally determined, respectively.

2.2 Hydraulic system

The hydraulic system shown in figure 4 is comprised of an external gear pump, two single-rod cylinders, a pressure relief valve, a pilot operated pressure reducing valve, a bladder accumulator, a fine pressure filter, check valve, oil cooler and two 4/3 way proportional directional valves. The proportional directional valve used in this plant is a product with WREE6E322X/G24K31/A1V

Figure 3. Control schema of path and position control module FM-357-2.

Figure 4. Hydraulic circuit diagram of the system.

Figure 5. Evaluation of circular deviation G : (+) centre of minimum zone circles, (0) starting point, (1) minimum zone circles, (2) actual path (ISO 230-4 1996).

order code from Bosch Rexroth Company, is NS6 size and operates within the range of ± 10 Volt.

2.3 Circularity error

Circularity error is measured based on circular deviation error in the ISO 230-4 standard called 'circular tests for numerically controlled machine tools' *circular deviation (G)*: minimum radial separation of two concentric circles enveloping the actual path (minimum zone circles) as shown in figure 5 and which may be evaluated as the maximum radial range around the least squares circle (ISO 230-4 1996).

3. Statistical analysis

A full factorial design is used to determine the effects of piston diameter, inertia load, radius and feed rate on circularity error (C_e) in the hydraulic driven circular interpolation motions. The factors and factor levels are summarized in table 1, yield 108 runs ($3 \times 3 \times 4 \times 3$).

These runs are replicated for four times and their means are used as responses in statistical analysis. All the statistical processes are carried out for a significant level of 0.05, i.e., for a confidence level of 95% via Minitab commercial software. Table 2 shows the average experimental results obtained based on the experimental design.

3.1 Analysis of variance (ANOVA)

An ANOVA is used on the collected data for investigating the main effects of the piston diameter, inertia load, radius and feed rate and their corresponding two-level interaction effects on the circularity error. ANOVA test results for circularity error are given in table 3.

The statistical significance of the factors and their interactions on the response are determined according F-test values in ANOVA table. This process is carried out by comparing the F test value of the parameter with the standard F table value ($F_{0.05}$) at the 5% significance level. If F test value is greater than $F_{0.05}$ value, the process parameter is considered significant. Accordingly, the inertia load-feed rate interaction does not have a significant effect on the circularity error. In contrast, all the other factors and their interactions have a significant effect on the error. In the last column of the ANOVA table, percentage contribution of each parameter on the circularity error is given. Accordingly, Piston diameter has the greatest effect on the circularity error change and it is followed by radius, feed rate, piston diameter–radius, radius–feed rate, piston diameter–feed–rate, inertia load, piston diameter–inertia load, and inertia load–radius factors and interactions.

Table 1. Factors and their levels.

Factors	Units	Levels			
		1	2	3	4
Piston diameter, Dp	(mm)	40	50	63	–
Inertia load, W	(kg)	12,5	25	50	–
Radius, R	(mm)	5	10	20	40
Feed rate, F	(mm/min)	50	200	800	–

Table 2. Experimental results.

Run order	Dp	W	R	F	Experimental values	Run order	Dp	W	R	F	Experimental values
1	40	12.5	5	50	0.94540	55	50	25.0	20	50	0.56544
2	40	12.5	5	200	1.00532	56	50	25.0	20	200	0.61361
3	40	12.5	5	800	1.07599	57	50	25.0	20	800	0.69503
4	40	12.5	10	50	1.36512	58	50	25.0	40	50	0.60756
5	40	12.5	10	200	1.37741	59	50	25.0	40	200	0.77145
6	40	12.5	10	800	1.57892	60	50	25.0	40	800	0.94047
7	40	12.5	20	50	1.37535	61	50	50.0	5	50	0.42214
8	40	12.5	20	200	1.57909	62	50	50.0	5	200	0.48218
9	40	12.5	20	800	1.85280	63	50	50.0	5	800	0.53554
10	40	12.5	40	50	1.45602	64	50	50.0	10	50	0.54209
11	40	12.5	40	200	1.71341	65	50	50.0	10	200	0.58071
12	40	12.5	40	800	2.06024	66	50	50.0	10	800	0.54638
13	40	25.0	5	50	0.93854	67	50	50.0	20	50	0.60565
14	40	25.0	5	200	0.99631	68	50	50.0	20	200	0.66957
15	40	25.0	5	800	1.10841	69	50	50.0	20	800	0.78755
16	40	25.0	10	50	1.17214	70	50	50.0	40	50	0.81843
17	40	25.0	10	200	1.18986	71	50	50.0	40	200	0.91412
18	40	25.0	10	800	1.48582	72	50	50.0	40	800	1.12158
19	40	25.0	20	50	1.32283	73	63	12.5	5	50	0.36329
20	40	25.0	20	200	1.65091	74	63	12.5	5	200	0.39502
21	40	25.0	20	800	1.78900	75	63	12.5	5	800	0.44297
22	40	25.0	40	50	1.47082	76	63	12.5	10	50	0.38631
23	40	25.0	40	200	1.76421	77	63	12.5	10	200	0.42612
24	40	25.0	40	800	2.14344	78	63	12.5	10	800	0.44591
25	40	50.0	5	50	0.91475	79	63	12.5	20	50	0.43156
26	40	50.0	5	200	0.99276	80	63	12.5	20	200	0.51125
27	40	50.0	5	800	1.12071	81	63	12.5	20	800	0.57825
28	40	50.0	10	50	1.17543	82	63	12.5	40	50	0.52208
29	40	50.0	10	200	1.27684	83	63	12.5	40	200	0.90807
30	40	50.0	10	800	1.45419	84	63	12.5	40	800	0.94595
31	40	50.0	20	50	1.37004	85	63	25.0	5	50	0.36817
32	40	50.0	20	200	1.67167	86	63	25.0	5	200	0.38910
33	40	50.0	20	800	1.71223	87	63	25.0	5	800	0.44754
34	40	50.0	40	50	1.47350	88	63	25.0	10	50	0.38620
35	40	50.0	40	200	1.75403	89	63	25.0	10	200	0.49902
36	40	50.0	40	800	2.08933	90	63	25.0	10	800	0.53371
37	50	12.5	5	50	0.42375	91	63	25.0	20	50	0.47051
38	50	12.5	5	200	0.45155	92	63	25.0	20	200	0.51396
39	50	12.5	5	800	0.51141	93	63	25.0	20	800	0.62492
40	50	12.5	10	50	0.45404	94	63	25.0	40	50	0.52649
41	50	12.5	10	200	0.53756	95	63	25.0	40	200	0.86618
42	50	12.5	10	800	0.52726	96	63	25.0	40	800	0.96533
43	50	12.5	20	50	0.54863	97	63	50.0	5	50	0.35404
44	50	12.5	20	200	0.66051	98	63	50.0	5	200	0.40606
45	50	12.5	20	800	0.68442	99	63	50.0	5	800	0.43200
46	50	12.5	40	50	0.51446	100	63	50.0	10	50	0.46963
47	50	12.5	40	200	0.73566	101	63	50.0	10	200	0.57812

Table 2. (continued.)

Run order	Dp	W	R	F	Experimental values	Run order	Dp	W	R	F	Experimental values
48	50	12.5	40	800	0.76392	102	63	50.0	10	800	0.47864
49	50	25.0	5	50	0.39041	103	63	50.0	20	50	0.46144
50	50	25.0	5	200	0.47547	104	63	50.0	20	200	0.63539
51	50	25.0	5	800	0.53274	105	63	50.0	20	800	0.57646
52	50	25.0	10	50	0.47196	106	63	50.0	40	50	0.47686
53	50	25.0	10	200	0.56628	107	63	50.0	40	200	0.93532
54	50	25.0	10	800	0.54397	108	63	50.0	40	800	1.11076

3.2 Main effects of control factors on the circularity error

Considering figure 6 and means of experimental results, the following points are obtained.

- According to experimental plan, while the minimum circularity error ($Ce_{average} = 0.35404$) is obtained with piston diameter of 63 mm, inertia load of 50 kg, radius of 5 mm, and the feed rate of 50 mm/min, the maximum circularity error ($Ce_{average} = 2.17947$) is obtained with the piston diameter of 40 mm, inertia load of 50 kg, the radius of 40 mm and the feed rate of 800 mm/min.
- It is obvious that the piston diameter has the most significant effect on the circularity error. In the experiments done with the piston diameter of 40 mm the highest error ($Ce_{average} = 1.4357$ mm) is obtained. In contrast, in the cylinders with the piston diameters of 50 mm ($Ce_{average} = 0.6085$ mm) and 63 mm ($Ce_{average} = 0.5517$ mm), error reductions of 57.62% and 61.57% are observed, respectively. In this case, it is clearly seen that there is a positive correlation between the piston diameter and the positioning accuracy, which is also parallel with the literature. In addition, assigning a different Kv value to each cylinder while setting the FM 357-2 controller is considered to be the cause of this condition.
- The inertia load does not have a very significant effect on the error compared to the other factors. The highest errors ($Ce_{average} = 0.8947$ mm) are obtained in the experiments done

Table 3. ANOVA test results.

Source	DF	SS	MS	F-test	F _{0,05}	P
Dp	2	17.62672	8.81336	2563.59	3.13	72.93
W	2	0.04836	0.02418	7.03	3.13	0.20
R	3	3.73942	1.24647	362.57	2.74	15.47
F	2	1.10771	0.55385	161.10	3.13	4.58
DpxW	4	0.04474	0.01118	3.25	2.51	0.19
DpxR	6	0.72402	0.12067	35.10	2.24	3.00
DpxF	4	0.19248	0.04812	14.00	2.51	0.80
WxR	6	0.05543	0.00924	2.69	2.24	0.23
WxF	4	0.00745	0.00186	0.54	2.51	0.03
RxF	6	0.38839	0.06473	18.83	2.24	1.61
Error	68	0.23378	0.00344	—	—	0.97
Total	107	24.16849	—	—	—	100

DF: Degrees of freedom, SS: Sum of squares, MS: Mean squares, P: Percentage contribution

Figure 6. Main effects plot for C_e .

with the inertia load of 50 kg. However, in the inertia loads of 12.5 kg and 25 kg, error reductions of 5.47% and 4.38% are obtained, respectively.

- As it can be seen from both the results of ANOVA and the graphics in figure 6, the most effective parameter on the circularity error after the piston diameter is the radius. The highest positioning errors ($C_{e\text{average}} = 1.1323$ mm) are obtained in the experiments done with the radius of 40 mm. In contrast, in the values of 5, 10 and 20 mm, the reductions of 44.63%, 31.08% and 18.60% are seen, respectively.
- Feed rate has the third most significant effect on the error. The highest positioning error values ($C_{e\text{average}} = 0.9826$ mm) are obtained in the experiments done with the feed rate of 800 mm/min. However, in the feed rates of 50 ($C_{e\text{average}} = 0.7355$ mm) and 200 mm/min ($C_{e\text{average}} = 0.8780$ mm), the error reductions of 25.15% and 10.65% are observed, respectively.
- It is clear from the main effects graph that circularity error increases with the increase of inertia load, radius and feed rate, and declines with the decrease of piston diameter.
- Lastly, when the main effects graph is taken into account, it is expected that minimum circularity error must be obtained in the third level of piston diameter ($D_p = 63$ mm), and in the first levels of inertia load ($W = 12.5$ kg), radius ($R = 5$ mm) and feed rate ($F = 50$ mm/min). In the three confirmation tests conducted in this condition, average 0.345 mm circularity error is obtained. The difference between this condition and the experimental plan can be explained by the compensation of the load changes via proposed system successfully.

3.3 Effects of factor interactions on the circularity error

Figure 7 shows the effects of two-way interactions on the C_e circularity error. According to this:

- In the piston diameter–inertia load interaction, the piston diameter is quite dominant. In each piston diameter there is not much change in the error in all levels of inertia load. When the piston diameter axis of the graphic is examined, there is not a clear change in the error in the piston diameters of 50 and 63 mm while there is a dramatic increase in 40 mm.
- Figure 7b illustrates the effect of piston diameter–radius interaction on the error. Especially, in the piston diameter of 40 mm and the radius of 40 mm the error reaches the peak point. There is a steady increase in the increasing values of the radius and in all the levels of piston diameter.

Figure 7. 3D Surface plot of factor interactions on the circularity error (Ce).

- The graphic of piston diameter–feed rate interaction shows irregular and non-linear characteristics (figure 7c). While a soft error decrease is obtained in the feed rate of 50 mm/min and the piston diameters of 40, 50 and 63 mm, there is a dramatic decrease in the middle of the graphic (condition: $F = 200$ mm/min and $Pd = 50$ mm). Also, it is clearly seen that the error reaches the peak point on the left end point of the graphic (condition: $Pd = 40$ mm and $F = 800$ mm/min).
- Inertia load–radius interaction does not have an important effect on the circularity error. In addition, radius is more effective on the error and as the radius goes up in all the levels of inertia load, the error increases (figure 7d).
- The inertia load–feed rate interaction has the least effect on the circularity error (statistically insignificant).
- In figure 7f, the minimum circularity error is obtained in the feed rate of 50 mm/min and the radius of 5 mm, and the maximum circularity error in the feed rate of 800 mm/min and the radius of 40 mm. It is clear that the radius is more dominant than the feed rate on the circularity error in this interaction.

4. Conclusions

A new positioning system was constructed by connecting the mechanic structure driven by hydraulic cylinders with the FM 357-2 analogue function module previously used in the control of the four-axis CNC machine tools. The mechanic structure consists of twin-axis assembled at 90° similar to the X and Y axes configuration of the CNC vertical machining center. As a result of the statistical analyses based on the full factorial design, the following conclusions have been given:

- According to confirmation test results, minimum circularity error is obtained with the piston diameter of 63 mm, inertia load of 12.5 kg, radius of 5 mm, and the feed rate of 50 mm/min as 0.345 mm.

- Circularity error increases with the increase of inertia load, radius and feed rate, and decreases with the decrease of piston diameter.
- According to ANOVA results, the most significant factor is piston diameter followed by the factors and interactions of radius, feed rate, piston diameter–radius, radius–feed rate, piston diameter–feed rate, inertia load, piston diameter–inertia load, and inertia load–radius according to their significance sequence.
- It is obvious that when the piston diameter increases, the circularity error decreases, which also shows parallelism in the related literature. Additionally, it is considered that the most important reason for the dramatic effect of the piston diameter on the error and it is being more significant than the other factors is the necessity of selecting different K_v values for each piston diameter.
- Lastly, the use of the system is proposed for mining, furniture, marble, welding and wood working sectors which do not require high positioning accuracy. As a future work, the system will be modified by using servo valve, 0.001 mm sensitivity linear encoder and hydraulic driven motor instead of employed equipments.

Acknowledgement

This study was supported by Gazi University Scientific Researches Projects Commission with this contract number 07/2003–20.

Nomenclature

K_v	Control gain
V	Velocity
Δs	Following error
G	Circular deviation
C_e	Circularity error
D_p	Piston diameter
W	Inertia load
R	Radius
F	Feed rate

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