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OPTIMIZING THE CONTOURING ACCURACY OF CNC MILLING MACHINE WITH DOUBLE BALL BAR TEST

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Abstract: In recent years, an instrumentation circular profile tests has been specified to assess the contouring accuracy of CNC machine tools. Such an instrumentation type test is the Double Ball Bar (DBB) test. In this paper, the influence of the position loop gain and mismatch of position loop gains for different machine axes are effectively studied. This work outlines a practical procedure for determining the position loop gain of the control system in order to minimize the resulting contouring errors.
Keywords: contouring accuracy, CNC machine, Double Ball Bar (DBB) test

INTRODUCTION

The contouring performance of CNC machine tool can be established by assessing its ability to move along a specified profile by the simultaneous movement of two or more axes.

When CNC machine tools are used for contouring applications, especially where high feed rates are used, significant dynamic errors can be introduced by the characteristics of the CNC controller and servo feed drive system. The assessment of such dynamic errors in CNC machines has traditionally been undertaken by machining a standard circular test piece. Such a test piece is outlined in some of the national machine tool standards American [1], British [2], where the circular profile is produced by the simultaneous motion of two linear axes.

An alternative approach to the machining test, specified in British and US machine tool standards, is emulation by instrumentation techniques of the circle test ISO 230-4 [3].

Such an instrument type test is Double Ball Bar (DBB) test. Bryan [4] first developed the Double Ball Bar (DBB) method to inspect CNC machines contouring behavior.

Although instrumentation techniques generally check the machine in no-load condition, they offer certain advantages over cutting conditions. In particular, tools and test specimens are not consumed and the time consumed in metrologising the test piece after machining is eliminated.

THE CONTISURE DOUBLE BALL BAR (DBB) HARDWARE AND SOFTWARE SYSTEM

On the market there are several commercially available Double Ball Bar (DBB) systems. The CONTISURE Double Ball Bar (DBB) system is developed by Burdekin [5,6].

The CONTISURE Double Ball Bar (DBB) system is shown schematically in figure1.

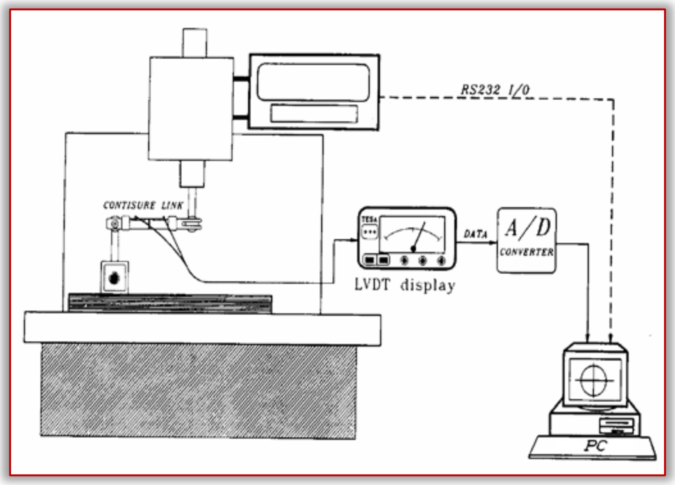

Figure 1. CONTISURE Double Ball Bar (DBB) system hardware set-up on CNC milling machine

The system comprises two high precision reference spheres, rigidly mounted at the spindle and table positions. A transducer link of carbon fiber construction and containing two precision transducers is located kinematically between the two reference spheres.

These two transducers contact directly onto the two spheres, and the summation of their outputs represents the change in distance of the two reference spheres, as the machine performs a circular contouring operation. The absolute distance between the two spheres can be established by setting the transducer link against a calibrated setting block. This feature, which is unique to the CONTISURE Double Ball Bar (DBB) system, ensures the complete traceability of data to be maintained.

The data acquisition and analysis software offer the user a complete flexibility. The number of sampled data points can be selected, up to a maximum of 12000 per 360 degrees scan. An analysis in the form of least squares best fit circles, can also be perform on data obtained for 360 degrees scans as well as for partial arcs. This feature eliminates the need for precise set-up of the sphere datum with respect to the programmed circle.

It is also essential that the start and end points of the circular contour should be selected, so that these do not coincide with the axis reversal points. The reason for this is that significant lost motion errors may occur at these points, and additional transients errors, resulting from the servo control system, may not be detected. In this respect the software is completely flexible and enables the start and end points to be freely selected. A start position of 22 degrees from the X-axis was therefore used for all tests.

The approach to the start point of the circular profile should, if possible, be representative of that used under practical machining conditions. The software therefore assumes a tangential approach to the start and exit points on the profile.

INFLUENCE OF THE POSITION LOOP GAIN AND MISMATCH OF THE POSITION LOOP GAINS FOR DIFFERENT MACHINE AXES ON OPTIMIZING THE CONTOURING ACCURACY OF CNC MILLING MACHINE

One of the most important factors which influences the dynamical behavior of the feed drives for CNC machine tools is position loop gain or Kv factor. Tracking or following error depends on the magnitude of the Kv-factor. In multi-axis contouring the following errors along the different axes may cause form deviations of the machined contours. Generally, position loop gain Kv should be high for faster system response and higher accuracy, but the maximum allowable gains are limited due to undesirable oscillatory responses at high gains and low damping factor which produce significant transient errors and accuracy started to decrease again. Usually Kv factor is set up by the machine tool manufacturer

But the question is whether the set-up value of the Kv-factor is always optimal? Generally, contouring error of circular contour, according [7-12], could be analytically approximately calculated with following equations:

$$ec=\left|R\cdot\left\{1-\sqrt{1+\frac{1}{2}\cdot\left(\frac{v}{60\cdot R\cdot Kv}\right)^2\left[1+\frac{1}{(1-a)^2}-\frac{60\cdot a\cdot R\cdot Kv}{v\cdot(1-a)}\right]}\right\}\cdot 10^3\right| \ \mu m \quad (1)$$

where: ec-maximal contouring error from the nominal radius μm, R-radius of the circle mm, v-feed rate mm/min, Kv-position loop gain s^{-1}, a-mismatch of position loop gains for different machine axes (a=(Kvx-Kvy)/Kvx and Kvx=Kv, Kvx-X axis position loop gain s^{-1}, Kvy-Y axis position loop gain s^{-1}).

If Kvx=Kvy, a=0 and equation (1) is transformed in:

$$ec=\left|R\cdot\left[1-\sqrt{1+\left(\frac{v}{60\cdot R\cdot Kv}\right)^2}\right]\cdot 10^3\right| \ \mu m \quad (2)$$

Similar equations are given in [13,14]. These equations do not take into consideration the influence of nonlinear phenomena, such as lost motion, stick motion and stick-slip, etc. on the magnitude of the contouring errors [15,16,17,18,19,20], which can cause a significant difference between theoretically calculated and experimentally obtained results (see table 1 and table 2).

Experimental contouring measurements with CONTISURE Double Ball Bar (DBB) test equipment have been undertaken on a FGS32 CNC milling machine with HEIDEHANN 355 TNC controller, in order to illustrate a methodology which could generally be applied to any CNC machine. Only two sets of axes have been considered (X and Y). The same procedure can be repeated for other axes. A relatively short link of 150 mm was used for all tests.

In the tests the feedrate was constant v=600 mm/min, radius of the circle was R=150 mm, mismatch of position loop gains for different machine axes was a=0 and the Kv factor in the controller was changed in the range of 4 s^{-1} to 130 s^{-1}. The tests were done in two directions clockwise (CW) and counterclockwise (anticlockwise) (CCW). The results of tests are given in table 1.

From Table 1 it is obvious that optimal experimental value for Kv factor is 100 s^{-1}. Kv factor set up by the machine manufacturer, was 28.3 s^{-1}.

We can see that increasing position loop gain Kv in the range of 4 to 100 s^{-1} decreases maximal contour deviation from nominal radius. Also we can see that the values for Kv in the range of 110 to 130 s^{-1} increase contouring error. This can be explained by the fact that transient errors become dominant. Further analyses shows that with increasing the position loop gain from 28.3 to 100 s^{-1} the maximal contouring deviation decreases from 19.6 (CW)/22.2 (CCW) μm to 10.2 (CW)/10.2 (CCW) μm. Figures 2-5 show graphically some results of the experiments.

In reference [21-23] an analytical equation for estimating position loop gain Kv is given:

$$Kv=\frac{1}{4D^2\cdot\left(\frac{2D_e}{\omega_e}+\frac{2D_m}{\omega_m}+\frac{T}{2}\right)} \quad (3)$$

where D-position loop damping, ω_e -nominal angular frequency of the feed drive electrical parts s^{-1}, D_e -damping of the feed drive electrical parts, ω_m -nominal angular frequency of the mechanical transmission elements s^{-1}, D_m -damping of the mechanical transmission elements and T-sampling period s.

Table 1. Influence of the position loop gain Kv on the magnitude of maximal contouring error from the nominal radius

Kv s^{-1}	4	6	8	10
ec µm (CW) experimentally	46.8	39.5	38.3	32.2
ec µm (CCW) experimentally	50.7	45.5	37.5	35.2
ec µm analytically with eq. (2)	20.8	9.26	5.21	3.33
Kv s^{-1}	20	28.3	30	40
ec µm (CW) experimentally	20.7	19.6	16.5	14.7
ec µm (CCW) experimentally	25.2	22.2	20.3	17.8
ec µm analytically with eq. (2)	0.83	0.42	0.37	0.21
Kv s^{-1}	50	60	70	80
ec µm (CW) experimentally	13.6	12.1	11.1	10.8
ec µm (CCW) experimentally	13.3	12.4	10.8	10.7
ec µm analytically with eq. (2)	0.13	0.09	0.07	0.05
Kv s^{-1}	90	100	110	120
ec µm (CW) experimentally	10.5	10.2	10.3	10.4
ec µm (CCW) experimentally	10.4	10.2	10.4	10.5
ec µm analytically with eq. (2)	0.04	0.033	0.028	0.023
Kv s^{-1}	130			
ec µm (CW) experimentally	10.5			
ec µm (CCW) experimentally	10.6			
ec µm analytically with eq. (2)	0.02			

Position loop damping of D=0.707 is preferable according [24-31]. That is the value, which gives minimal contouring errors. Other numerical values of the examined system are: $\omega_e = 1000\,s^{-1}$, $D_e = 0.7$, $\omega_m = 663\,s^{-1}$, $D_m = 0.17$, and T=0.006 s. With the substitution in the equation (3) the position loop gain value Kv=106.35 s^{-1} is calculated.

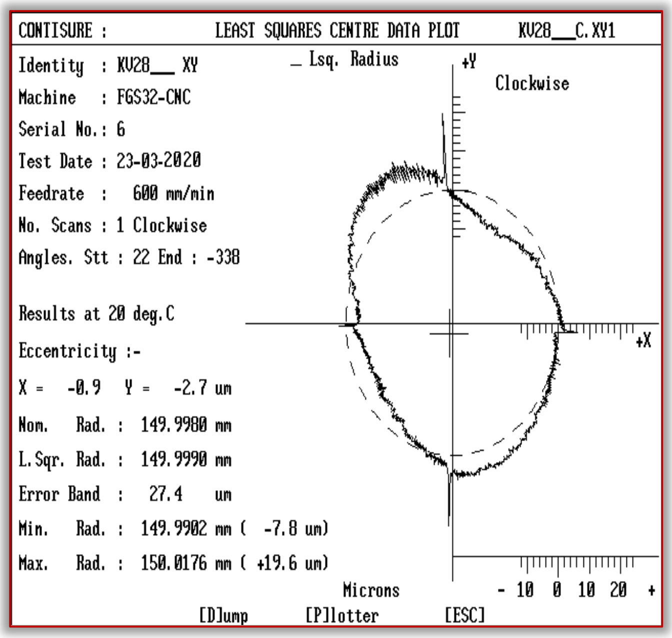

Figure 2. Polar diagram of the results of a measured circular test (feedrate v=600 mm/min, radius of the circle R=150 mm, position loop gain Kv=28.3 s^{-1}, a=0, clockwise direction).

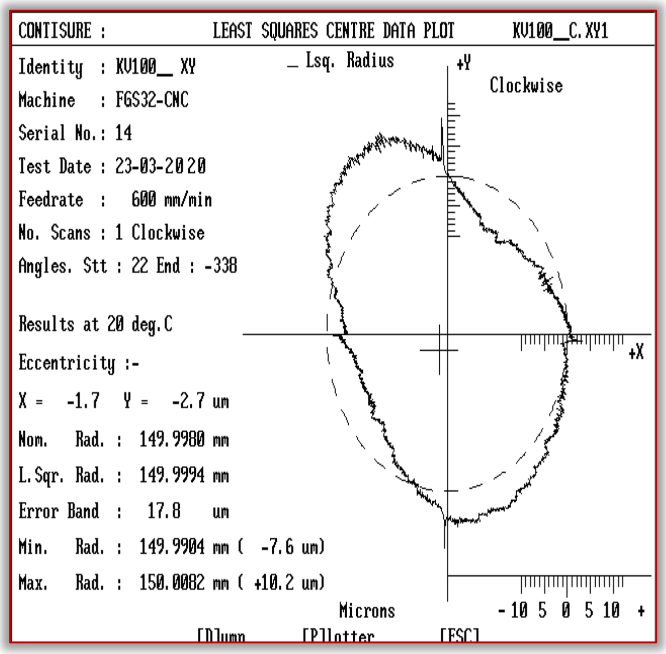

Figure 3. Polar diagram of the results of a measured circular test (feedrate v=600 mm/min, radius of the circle R=150 mm, position loop gain Kv=100 s^{-1}, a=0, clockwise direction)

The experimentally tuned value of Kv-factor on the examined machine tool axis was Kv=100 s^{-1}. The difference between analytically calculated and experimentally obtained value of Kv-factor is around 6.35%, which is acceptable for practical application.

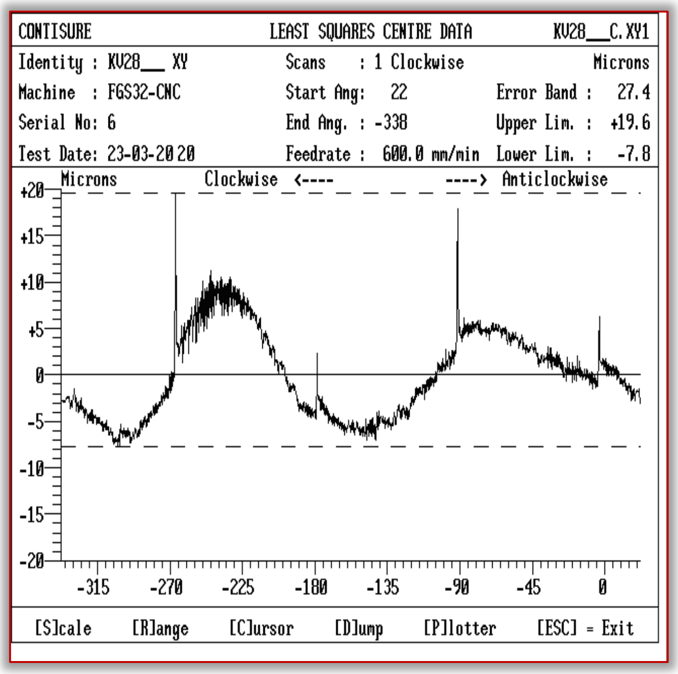

Figure 4. Linear diagram of the results of a measured circular test (feedrate v=600 mm/min, radius of the circle R=150 mm, position loop gain Kv=28.3 s^{-1}, a=0, clockwise direction)

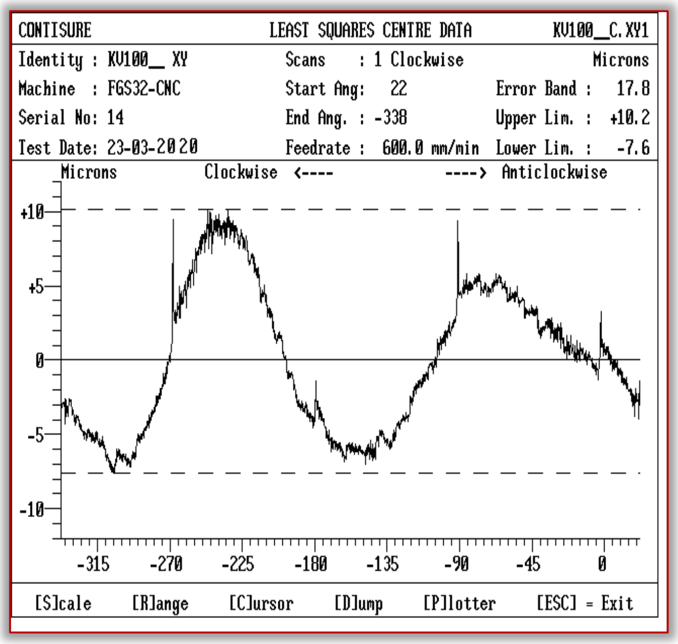

Figure 5. Linear diagram of the results of a measured circular test (feedrate v=600 mm/min, radius of the circle R=150 mm, position loop gain Kv=100 s^{-1}, a=0, clockwise direction)

Another parameter, which influences the contouring accuracy is the mismatch of position loop, gains for different machine axes. This will result in an elliptical contour path with the major axes lying +/-45 degrees, depending upon the direction of the scan, and increasing the contouring errors.

The results of the experiments with mismatching position loop gains $a=\frac{Kvx-Kvy}{Kvx}\cdot 100$ % are given in table 2. (Kvx=30 s^{-1}, R=150 mm and v=600 mm/min are constant.)

Table 2. Influence of the mismatching of the position loop gains on the magnitude of maximal contouring error from the nominal radius ec

a %	0	1	2	3
ec µm (CW) experimentally	14.5	17.8	17.9	18.3
ec µm (CCW) experimentally	16.5	19.7	19.9	20.3
ec µm analytically with eq. (1)	0	0.47	1.32	2.19
a %	4	5	6	7
ec µm (CW) experimentally	18.9	19.1	19.3	19.7
ec µm (CCW) experimentally	20.9	22.5	23.1	23.3
ec µm analytically with eq. (1)	3.08	3.99	4.92	5.87
a %	8	9	10	20
ec µm (CW) experimentally	20.2	20.7	22.1	38.7
ec µm (CCW) experimentally	25.4	27.5	29.4	52.9
ec µm analytically with eq. (1)	6.84	7.83	8.84	20.34
a %	30	40	50	
ec µm (CW) experimentally	69.5	113.2	170.9	
ec µm (CCW) experimentally	85.6	128.4	186.2	
ec µm analytically with eq. (1)	35.12	54.81	82.35	

It is obvious that with increasing the mismatch of position loop gains of the axes, the contouring error rises up. The best case is when the position loop gains are identical (a=0). Figures 6 and 7 show the results of circular test when the difference between position loop gains for X and Y axes is a=20%.

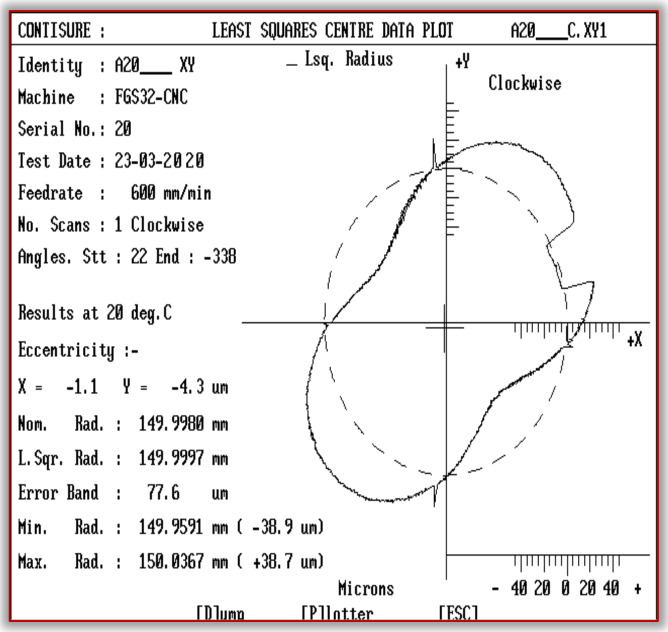

Figure 6. Polar diagram of the results of the measured circular tests with gains mismatched a=20% (clockwise direction, feedrate v=600 mm/min, radius of the circle R=150 mm, position loop gains Kvx=30 s^{-1} and Kvy=24 s^{-1})

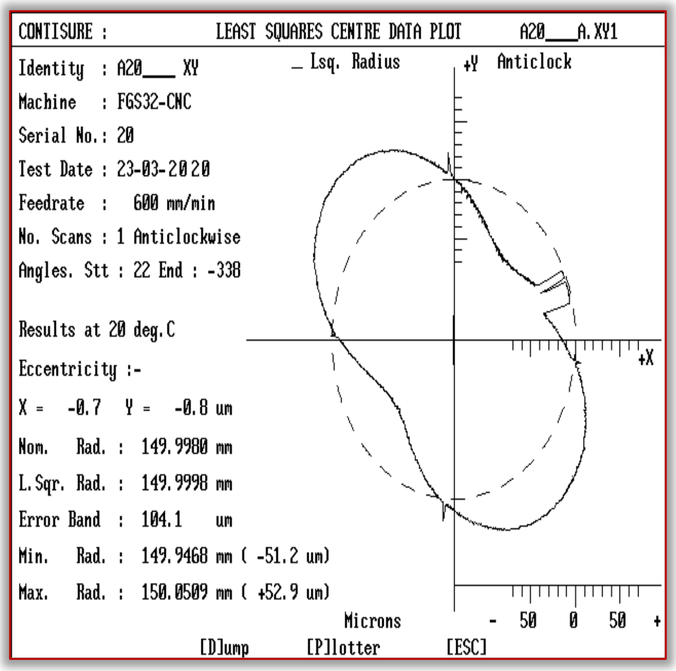

Figure 7. Polar diagram of the results of the measured circular tests with gains mismatched a=20% (anticlockwise direction, federate v=600 mm/min, radius of the circle R=150 mm, position loop gains Kvx=30 s^{-1} and Kvy=24 s^{-1})

CONCLUSION

The work has shown that the contouring errors in CNC machine tool can be minimized by appropriate selection of position loop gain in the controller. Criteria used in establishing the optimum Kv value was minimization of maximal contouring deviation from nominal radius.

The test methodology with CONTISURE Double Ball Bar (DBB) system, demonstrated on FGS32 CNC milling machine with HEIDEHANN controller, offers a general approach for experimental determining of a position loop gain.

It was shown that the best results in contouring accuracy are provided when the position loop gains for the two axes are identical.

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