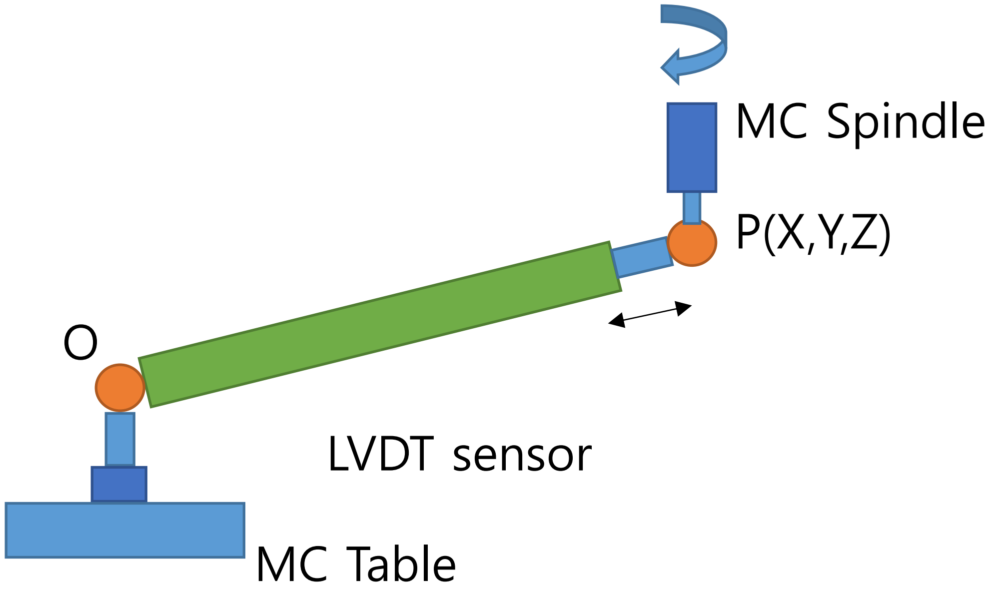
Precision Metrology 18

Contour Measurement using the Ball-Bar sensor

:To measure the contouring performance of machine during the contouring motion, in order to measure squareness, gain mismatch, and other geometric errors

Ball Bar sensor



-Let machine move in circular motion, then the radial displacement is measured.

-Perfect (or error free) machine will give perfect (ideal) circle corresponding to the nominal circle.

-Any deviation of the contour is due to some kinds of machine geometric error.

Let $(\Delta X, \Delta Y, \Delta Z)$ be the 3D errors that experienced at the $P(X,Y,Z)$ point with respect to the origin $O(0,0,0)$;

R = Nominal distance between OP

$=\sqrt{[X^2+Y^2+Z^2]}$

Ra= Actual distance between OP

$=\sqrt{[(X+\Delta X)^2+(Y+\Delta Y)^2+(Z+\Delta Z)^2]}$

$=\sqrt{[X^2+Y^2+Z^2+2X\Delta X+2Y\Delta Y+2Z\Delta Z+\Delta X^2+\Delta Y^2+\Delta Z^2]}$

$\fallingdotseq\sqrt{[X^2+Y^2+Z^2+2X\Delta X+2Y\Delta Y+2Z\Delta Z]}$

The measured data at the LVDT,

$\Delta R=Ra-R$

$=\sqrt{[X^2+Y^2+Z^2+2X\Delta X+2Y\Delta Y+2Z\Delta Z]}-\sqrt{[X^2+Y^2+Z^2]}$

$=R[1+\{2X\Delta X+2Y\Delta Y+2Z\Delta\}/R^2]^{1/2} - R$

$\fallingdotseq R[1+\{X\Delta X+Y\Delta Y+Z\Delta Z\}/R^2]-R$

$=(X\Delta X+Y\Delta Y+Z\Delta Z)/R$

Alternatively, the radial error component measured at the LVDT will be the inner product of the 3D error vector and the unit vector of the LVDT direction;

That is

$\Delta R=(\Delta X, \Delta Y, \Delta Z)\cdot(X,Y,Z) / \sqrt{(X^2+Y^2+Z^2)}$

$=(X\Delta X+Y\Delta Y+Z\Delta Z) / \sqrt{(X^2+Y^2+Z^2)}$

$=(X\Delta X+Y\Delta Y+Z\Delta Z) / R$

In 2D plane,

For measurement in the XY plane,

$\Delta R=(X\Delta X+Y\Delta Y)/R$

For measurement in the YZ plane,

$\Delta R=(Y\Delta Y+Z\Delta Z)/R$

For measurement in the ZX plane,

$\Delta R=(Z\Delta Z+X\Delta X)/R$

In the XY plane

(1) Squareness error

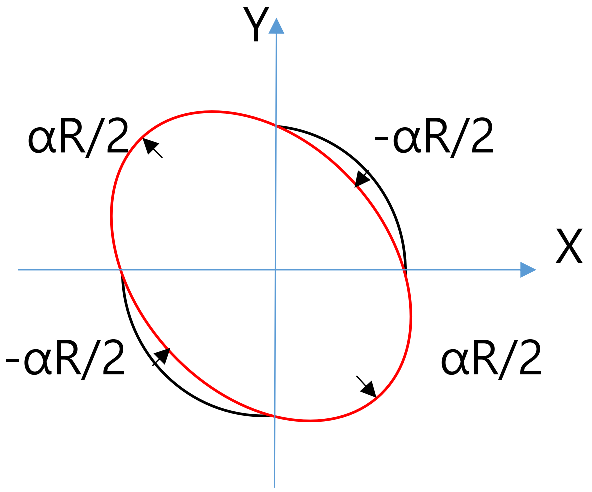
When α is the squareness error between XY axis, then

$\Delta X=0$, $\Delta Y=-\alpha X$;

Thus $\Delta R=Y\Delta Y/R=-\alpha XY/R=-\alpha R\cos\theta\sin\theta=-\alpha R\sin2\theta/2$

$\therefore$ $\Delta R(\theta)$ is an 45° rotated ellipse;

with $R+\alpha R/2$ major radius and $R-\alpha R/2$ minor radius



Graphical calculation

$\Delta R_{45°}=-\alpha R/2$ or

$\{\Delta R_{45°}+\Delta R_{225°}-\Delta R_{135°}-\Delta R_{315°}\}/4=-\alpha R/2$

∴Squareness error, $\alpha=-2\Delta R_{45^\circ}/R$ or

$-2\{\Delta R_{45^\circ}+\Delta R_{225^\circ}-\Delta R_{135^\circ}-\Delta R_{315^\circ}\}/4R$

Analytic calculation

$R(\theta)=R+\Delta R=R_0+\Sigma[A_k\cos k\theta+B_k\sin k\theta]$ for k=1 to n

Where $R_0=\int R(\theta)d\theta/2\pi \fallingdotseq \Sigma R_i/N$

$A_k=\int R(\theta)\cos k\theta d\theta/\pi \fallingdotseq 2\Sigma R_i\cos k\theta_i/N$

$B_k=\int R(\theta)\sin k\theta d\theta/\pi \fallingdotseq 2\Sigma R_i\sin k\theta_i/N$

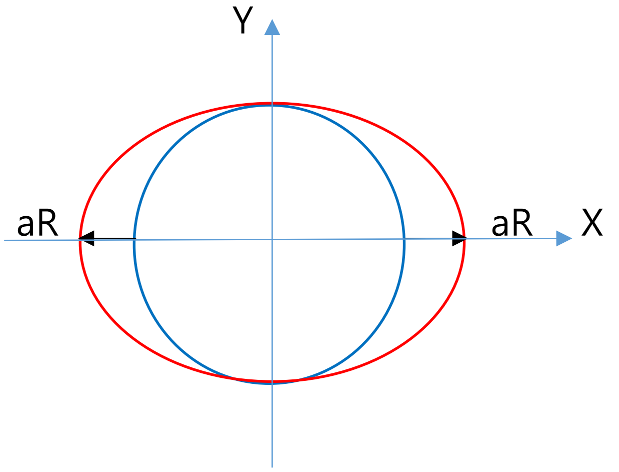
B_2 of $\sin 2\theta$ component = $-\alpha R/2$

∴ Squareness error, $\alpha=-2B_2/R$

(2) Positional error

When a is the positional error per unit length for the X axis; $\Delta X=aX$, $\Delta Y=o$

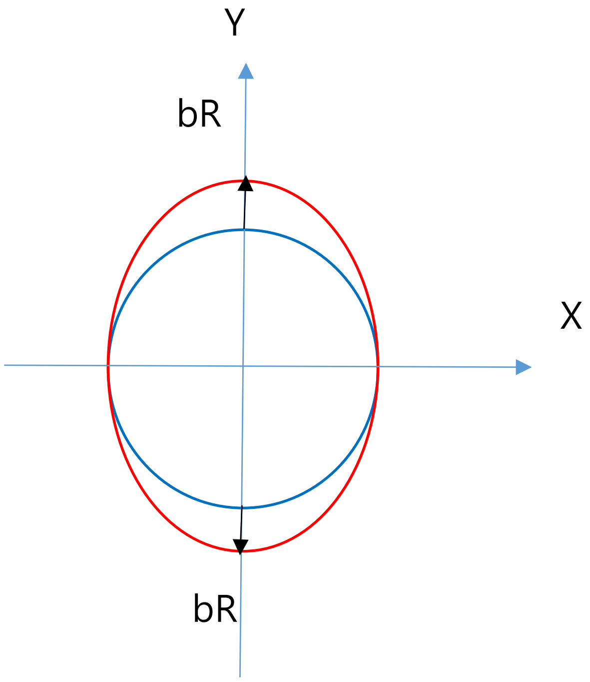
Thus $\Delta R=X\Delta X/R=aX^2/R=aR\cos^2\theta$



X positional error, $a=\Delta R_{0°}/R$ or $\{\Delta R_{0°}+\Delta R_{180°}\}/2R$

When b is the positional error per unit length for the Y axis; $\Delta Y=bY$, $\Delta X=0$

Thus $\Delta R=Y\Delta Y=bY^2/R=bR\sin^2\theta$



Y positional error, $b=\Delta R_{90°}/R$ or $\{\Delta R_{90°}+\Delta R_{270°}\}/2R$

(3) Servo gain mismatch

Let Kx, Ky be the servo gains for the X and Y axis, respectively.

Then the steady-state following error is introduced in X,Y axis respectively;

$\Delta X=-Vx/Kx$; where Vx, Kx are the velocity, gain for the X axis

$\Delta Y=-Vy/Ky$; where Vy, Ky are the velocity, gain for the Y axis

<u>CCW case</u>

Remembering $Vx=-F\sin\theta$, $Vy=F\cos\theta$ when F is the feeding velocity in the CCW direction;

$\Delta X=F\sin\theta/Kx$

$\Delta Y=-F\cos\theta/Ky$

Thus the radial error, ΔR, is

$\Delta R=(X\Delta X+Y\Delta Y)/R=[XF\sin\theta/Kx-YF\cos\theta/Ky]/R$

$=F\cos\theta\sin\theta/Kx-F\sin\theta\cos\theta/Ky$

$=F\cos\theta\sin\theta(Ky-Kx)/KxKy$

$=F\cos\theta\sin\theta\Delta K/KxKy$, where $\Delta K=Ky-Kx$=gain mismatch

∴ Ellipse with 135° rotated major axis

∴ $\Delta R_{135°CCW}=\alpha R/2+F\Delta K/KxKy$

<u>CW case</u>

For feeding velocity, F, in the CW direction, $Vx=F\sin\theta$, $Vy=-F\cos\theta$;

Thus $\Delta R=(X\Delta X+Y\Delta Y)/R=[-XF\sin\theta/Kx+YF\cos\theta/Ky]/R$

$=-F\cos\theta\sin\theta/Kx+F\sin\theta\cos\theta/Ky$

$=F\cos\theta\sin\theta(Ky-Kx)/KxKy$

$=-F\cos\theta\sin\theta\Delta K/KxKy$, where $\Delta K=Ky-Kx$=gain mismatch

∴ Ellipse with 45° rotated major axis

∴ $\Delta R_{135°CW}=\alpha R/2-F\Delta K/KxKy$

$\therefore$ $F\Delta K/K_xK_y = [\Delta R_{135°CCW} - \Delta R_{135°CW}]/2$, and

$\alpha R/2 = [\Delta R_{135°CCW} + \Delta R_{135°CW}]/2$

Therefore the squareness error and the error due to the servo gain mismatch can be calculated.

The average value from 45, 135, 225, 315; or B2 of the sin2θ component of Fourier expansion can be used identically.

(4) Backlash error

Let Bx, By be the backlash errors that give positive backlash values when the direction is changed from forward to backward on the X,Y axis, respectively;

$\Delta X = -Bx\,\mathit{Sign}[dX/dt]/2$, and $\Delta Y = -By\,\mathit{Sign}[dY/dt]/2$

where the *Sign*[ ] gives the positive sign if inside term is positive and vice versa.

Thus radial error,

$\Delta R = (X\Delta X + Y\Delta Y)/R$

$= -\cos\theta Bx\,\mathit{Sign}[dX/dt]/2 - \sin\theta By\,\mathit{Sign}[dY/dt]/2$

$\Delta R_{-0°}$=-Bx/2 (X forward)

and $\Delta R_{+0°}$=+Bx/2 (X backward)

Thus X backlash error =backward-forward

$=+Bx/2 - (-Bx/2) = Bx = \Delta R_{+0°} - \Delta R_{-0°}$

Similarly,

$\Delta R_{90-°}$=-By/2 (Y forward) and

$\Delta R_{90+°}$=+By/2 (Y backward)

Thus Y backlash error=backward-forward

$=By/2-(-By/2)=By= \Delta R_{90+°} - \Delta R_{90-°}$

Similarly, geometric errors in the YZ, ZX planes can be calculated. This method is very useful for the error diagnosis, verification, and compensation for various precision machines in relatively short period.

Detail evaluation of the geometric errors can be found, and typical examples are shown in the paper:

A New technique for volumetric error assessment of CNC machine tools incorporating the ball bar measurement and the 3D volumetric error model, H.J.Pahk, Y.S.Kim,, J.H.Moon, Int.J.Machine Tools and Manufacture, Vol37(11), 1583-1596, 1997

5.2. *Horizontal machining center*

Fig. 8 shows the raw data plot for the circular error measurement in XY, YX, and ZX planes, respectively, where the dotted line indicates a counterclockwise contour and the solid line indicates a clockwise contour. The raw data were analyzed by the developed system and the error components were evaluated as follows:
X positional error = 14.1 μm
Y positional error = 21.7 μm
Z positional error = 19.2 μm
Y straightness along X axis = − 2.2 μm
Z straightness along X axis = − 0.7 μm
X straightness along Y axis = − 5.7 μm
Z straightness along Y axis = − 7.6 μm
X straightness along Z axis = 0.3 μm
Y straightness along Z axis = − 2.3 μm
Y angular error along X axis = − 9.6 μrad
Z angular error along X axis = − 29.3 μrad
X angular error along Y axis = 101.3 μrad
Z angular error along Y axis = 76 μrad
X angular error along Z axis = 30.6 μrad
Y angular error along Z axis = 4.5 μrad
squareness error between XY axis = 7.8 μrad
squareness error between YZ axis = 107.3 μrad
squareness error between ZX axis = 147.3 μrad
backlash error in X axis = 5.9 μm
backlash error in Y axis = 5.1 μm
backlash error in Z axis = 5.8 μm
error due to servo gain mismatch between XY axis = − 6.2 μm
error due to servo gain mismatch between YZ axis = 1.5 μm
error due to servo gain mismatch between ZX axis = − 0.5 μm.

The analyzed error components were removed from the raw data of the circular measurement, and the residual circular errors were calculated then plotted. Fig. 9 shows the residual circular errors after removing the error components, giving remarkably reduced error pattern.

Therefore, the developed error analysis system has been found as an efficient tool for the error diagnosis of machine tools based on the kinematic ball bar measurement method.

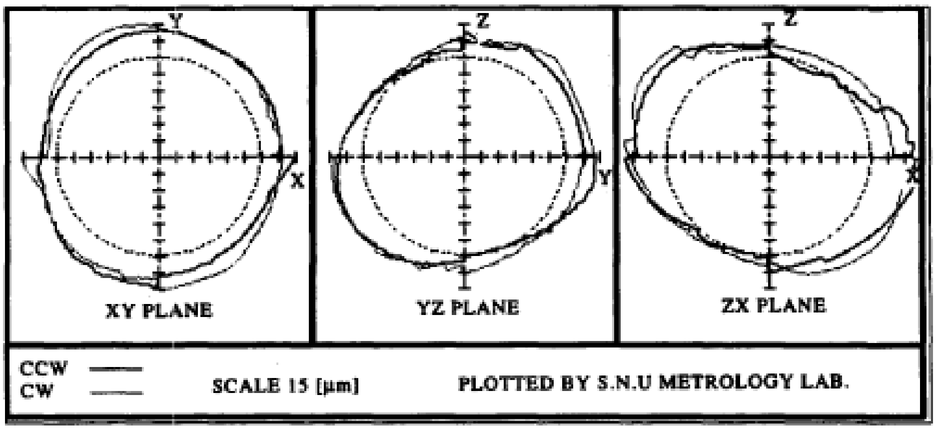


Fig. 8. Raw data plot for the ball bar measurement (horizontal machining center).