# APPLICATION OF A MAGNETIC BEARING SPINDLE TO NON-CIRCULAR FINE BORING

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## ABSTRACT

A magnetic bearing spindle is used in non-circular fine boring. The displacement of the rotor is controlled to follow a non-circular profile by the magnetic bearing. The reference trajectory of the rotor displacement is determined by choosing the axis trajectory having a lower frequency component and minimizing control current on the magnetic coils.

The periodic learning control with inverse transfer function compensation is applied to get the desired non-circular profile. This control technique, which is a type of feedforward control, can make periodic output errors converge to zero by repeatedly compensating the input data.

Several cutting tests are carried out for a non-circular piston pin bore by using the developed boring machine, which consists of a magnetic bearing spindle and a hybrid controller. The difference between the reference profile and the cutting profile was within 2 [$\mu$m] at a rotational speed of 25[rps] (1,500[rpm]).

## 1. Introduction

The non-circular shape in boring is sometimes desired for piston pin bores because the non-circular shape decreases the possibility of cracking inside piston pin bores during combustion in engine (Izumi, 1995). In order to realize non-circular boring, it is necessary to control the trajectory of the cutting tool. Magnetic bearings are well suited for this task because they can control cutting tool position.

Moreover the application of a magnetic bearing spindle to non-circular boring is expected to exhibit the following advantages:

(1) The low friction of magnetic bearings can realize high cutting speed.

(2) The high cutting speed means low cutting resistance, which is effective in the good surface finish of workpiece and the extension of tool life.

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(3) The cutting process can be monitored by observing the gap sensor signal and the current on coil.
(4) The maintenance of magnetic bearings is low.

Möller proposed the non-circular boring using a magnetic bearing spindle (Möller, 1990). He succeeded in manufacturing a non-circular bore at a rotational speed of 22500[rpm]. However, the details of the control method of reducing errors were not clarified enough.

The aim of this research is to realize the desired non-circular fine boring by applying the periodic learning control with inverse transfer function compensation to the control of a magnetic bearing spindle. This paper describes the followings:

- The calculation of reference trajectory of rotor displacement.
- The application of control technique for the accurate positioning of cutting tool.
- The developed fine boring machine.
- The experimental trajectory result.
- The cutting result.

## 2. Calculation of Reference Trajectory of Rotor Displacement

The reference profile in boring with magnetic bearing spindle is determined by the reference axis trajectory, which is achieved by controlling the rotor displacement. This section explains about the calculation of reference trajectory of rotor displacement.

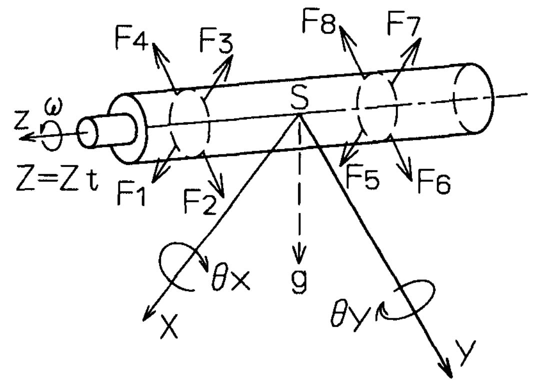
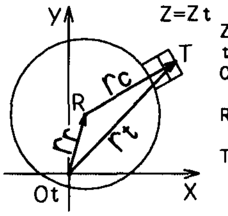


Fig.1 Basic Structure of Non-circular Boring with Magnetic Bearings and Definition of Coordinate System

$F_K$ : attractive force of electromagnet K
$T[x, y, z]$ : translational displacement of rotating body
$T[\theta x, \theta y]$ : angular displacement of rotating body
S : center of weight
g : acceleration of gravity



Zt : z-value of the location of the tool
tool-plane : Z=Zt
Ot : An intersecting point of tool-plane and z-axis
R(Xr, Yr) : position of the geometrical center of the rotor on tool-plane
T(Xt, Yt) : position of the vertex of the tool on tool-plane

$\overline{r_r} \triangleq \overline{OtR}$ (Trajectory of $r_r$ : axis trajectory on the tool-plane)
$\overline{r_c} \triangleq \overline{RT}$
$\overline{r_t} \triangleq \overline{OtT}$ (Trajectory of $r_t$ : tool-vertex trajectory on the tool-plane)

Fig.2 Vertex of Tool (T) on Tool-Plane (Z=Zt)

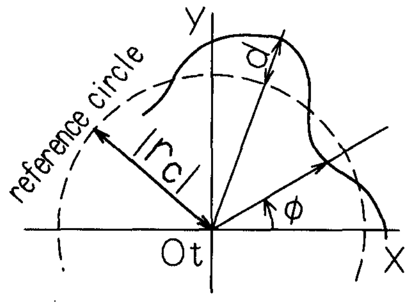


Fig.3 Definition of the Profile of Hole

## 2.1 Definition of Reference Profile

Figure 1 shows the basic structure of non-circular boring with magnetic bearings and the definition of coordinate system. Figure 2 defines symbols used in this section.

Figure 3 shows the definition of the profile of hole. In polar coordinate, we present the deviation $d$ from circle with radius $|\, r_c \,|$ as the function of $\phi$.

$$\tilde{d}\,(\phi) = \sum_{k=0}^{K} [\, \tilde{A}_{rk} \cdot \cos\,(\, k\phi \,+\, \tilde{P}_{rk}\,)\,] \tag{1}$$

where $\sim$ denotes reference value, $\tilde{A}_{rk}$ is the coefficient of the Fourier series and $\tilde{P}_{rk}$ is the phase angle.

The assumptions in this section are as follows:

(A1) The Rotor is rigid.
(A2) The Magnetic bearing has the dynamic stiffness sufficient to overcome cutting forces.
(A3) The Rotor rotates at constant angular velocity of $\omega$.
(A4) The value of $\tilde{A}_{rk}$ is very small as compared to $|\, r_c \,|$.
(A5) The reference profile is given by eq.(1).

## 2.2 Determination of Reference Axis Trajectory on Tool Plane

Let us consider the method to determine the reference axis trajectory when reference profile is given by eq.(1). From assumption (A3), $r_c$ is written as follows.

$$r_c\,(\phi) = |\, r_c \,| \cdot \exp\,(\, j\omega t\,) \tag{2}$$

$$\phi = \omega t \tag{3}$$

Two reference axis trajectories correspond to the reference profile given by eq.(1). They are given by eq.(4.a) and (4.b) (Higuchi, Otsuka and Ide, 1991).

$$\tilde{r}_{r1} = \sum_{k=0}^{K} \tilde{A}_{rk} \cdot \exp\,\,[\, j\,\{(+k+1)\,\omega t + \tilde{P}_{rk}\}] \tag{4$\cdot$a}$$

$$\tilde{r}_{r2} = \sum_{k=0}^{K} \tilde{A}_{rk} \cdot \exp\,\,[\, j\,\{(-k+1)\,\omega t - \tilde{P}_{rk}\}] \tag{4$\cdot$b}$$

We choose $\tilde{r}_{r2}$ because it has a lower frequency than $\tilde{r}_{r1}$. The reference axis trajectory on tool plane is determined as eq. (5) when the reference profile is given by eq.(1).

$$\tilde{r}_r = \sum_{k=0}^{K} \tilde{A}_{rk} \cdot \exp\,\,[\, j\,\{(-k+1)\,\omega t - \tilde{P}_{rk}\}] \tag{5}$$

This means that the frequency components of rotor movement become 0, - $\omega$, -2 $\omega$ respectively if the frequency components of the reference profile are $\phi$, 2 $\phi$, 3 $\phi$.

## 2.3 Calculation of Reference Trajectory of Rotor Displacement

There are many reference trajectories of rotor displacement to realize the reference axis trajectory. We choose a reference trajectory of rotor displacement to minimize control current (Higuchi, Otsuka and Tanaka, 1991):

$$\tilde{X}_a = [\, \tilde{x}_a, \tilde{y}_a \,] = \sum_{k=0}^{K} \tilde{A}_{ak} \cdot \exp\,\,[\, j\,\{(-k+1)\,\omega t - \tilde{P}_{ak}\}] \tag{6}$$

$$\tilde{X}_b = [\, \tilde{x}_b, \tilde{y}_b \,] = \sum_{k=0}^{K} \tilde{A}_{bk} \cdot \exp\,\,[\, j\,\{(-k+1)\,\omega t + \tilde{P}_{bk}\}] \tag{7}$$

(Subscripts *a* and *b* denote the radial magnetic bearing unit[*a*] and unit[*b*] respectively in Fig.6.)

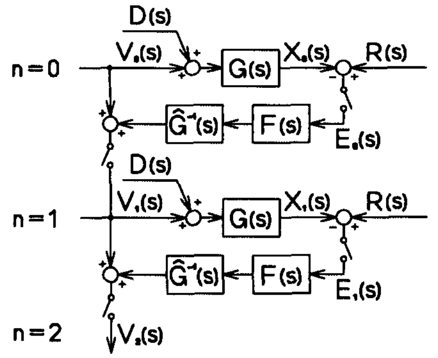


**Fig4** Block Diagram of Periodic Learning Control with Inverse Transfer Function Compensation

X(s) : output of the controlled system
V(s) : compensatory input ( $V_0(s)= R(s)\cdot\hat{G}^{-1}(s)$ )
R(s) : periodic reference input
E(s) : output error of the controlled system:= R(s)−X(s)
G(s) : closed loop transfer function of the controlled system, where X(s)= G(s)·V(s).
F(s) : filter which extracts only the fundamental component of the system.
D(s) : periodic disturbance
n : repetitive number of periodic learning control
( All subscripts denote the repetitive number. )

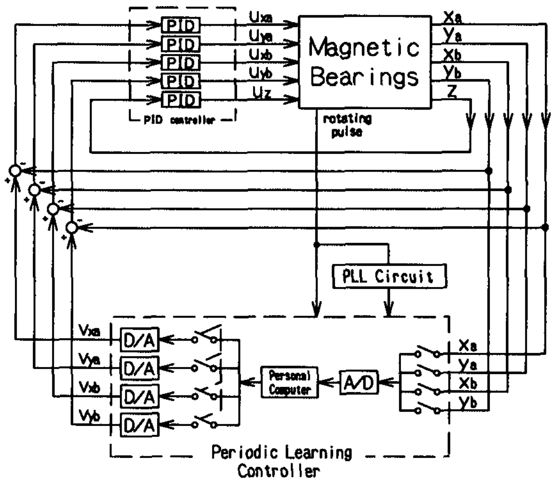


**Fig.5** Diagram of Control System

Vkj : compensatory signal in the k direction at unit j ( k=x, y and j=a, b )
Ukj : current signal in the k direction at unit j ( k=x, y, z and j=a, b )
Xj : output signal in the X direction at unit j ( j=a, b )
Yj : output signal in the Y direction at unit j ( j=a, b )
Z : output signal in the Z direction
( Subscripts a and b denote the radial magnetic bearing unit [a] and unit [b] respectively in Fig6. )

## 3. Periodic Learning Control with Inverse Transfer Function Compensation

### 3.1 Principles

Figure 4 shows a block diagram of the periodic learning control (PLC) with Inverse Transfer Function Compensation (ITFC) (Higuchi et al., 1990). Let us now explain the PLC with ITFC of one degree of freedom for the sake of brevity. The PLC with ITFC can make periodic output errors converge to zero by repeatedly adding the errors in the last period to the control input in the next period.

The output error of the n<sup>th</sup> repetition is given by

$$E_n(s)=-G(s)\cdot\{1-\hat{G}^{-1}(s)\cdot F(s)\cdot G(s)\}^{n}\cdot\{V_0(s)+D(s)\}+\{1-\hat{G}^{-1}(s)\cdot F(s)\cdot G(s)\}^{n}\cdot R(s) \qquad (8)$$

Symbol ˆ added to $G^{-1}(s)$ denotes that $G^{-1}(s)$ may have some errors. While the filter $F(s)$ is not always necessary for the basic form of the PLC with the ITFC, $F(s)$ is employed here in order to deal only with the fundamental component of the output error $E(s)$.

The output error converges to zero when the following equation is satisfied:

$$|\,1-\hat{G}^{-1}(s)\cdot F(s)\cdot G(s)\,|<1 \qquad (9)$$

When the filter $F(s)$ extracts only the component of frequency $\omega$, eq.(8) yields

$$|\,1-\hat{G}^{-1}(j\omega)\cdot G(j\omega)\,|<1 \qquad (10)$$

If eq.(10) is satisfied, the error of an angular velocity $\omega$ converges to zero.

### 3.2 Application to Non-circular Boring

For fine non-circular boring, the cutting profile must coincide with the reference profile accurately. To decrease the profile control error, the PLC with ITFC will be applied here.

The diagram of a control system is shown in Fig.5. The controlled system corresponds to a closed loop system which consists of magnetic bearings stabilized by the PID-controller in Fig.5. The definition of the coordinates is shown in Fig.1. A symbol $u_{kj}$(current control signal) in Fig.5 represents a signal of control force in the $k$ direction ($k$=$x$,$y$,$z$) of unit $j$ ($j$=$a$,$b$). (See Fig.6) Coil-current in each electromagnet is determined from these control current signals.

The PL-controller shown in Fig.5, which consists of a personal computer, an A/D converter, and four D/A converters, is added to the controlled system to carry out the PLC with ITFC. The PL-controller samples the output errors of the controlled system, carries out the calculation of $F(s)$ and $\hat{G}'(s)$ (See Fig.4), and adds the compensatory inputs to the controlled system .

The reference inputs to the controlled system correspond to the reference profile for non-circular boring. Because the PLC with ITFC makes the output errors of the controlled system converge to zero, what is treated as the output determines the effect of the PLC with ITFC. For the fine non-circular boring, when the signal corresponding to the cutting profile is treated as the output, the PLC with ITFC decreases the profile control error.

Applying the PLC with the ITFC in magnetic bearings has some good properties (Higuchi, Otsuka and Mizuno, 1990):

1) The PLC with ITFC makes the output errors converge to zero even when parameters of the controlled system are not accurately identified.
2) The implementation of the PLC with the ITFC is easily accomplished by adding a digital controller to a conventional (analog) PID-controller.
3) The PLC with the ITFC does not affect the stability of magnetic bearings at all.

## 4. Non-Circular Fine Boring Machine

Figure 7 shows the block diagram of the non-circular fine boring machine. The Non-circular boring machine is composed of a NC machine and a magnetic bearing spindle with a hybrid controller. The hybrid controller consists of a conventional PID analog controller and a digital controller. The PID controller is used for stabilizing the magnetic bearing system. The digital controller, consisting of a personal computer, an A/D converter and four D/A converters, is used for controlling the trajectory of the cutting tool in non-circular machining.

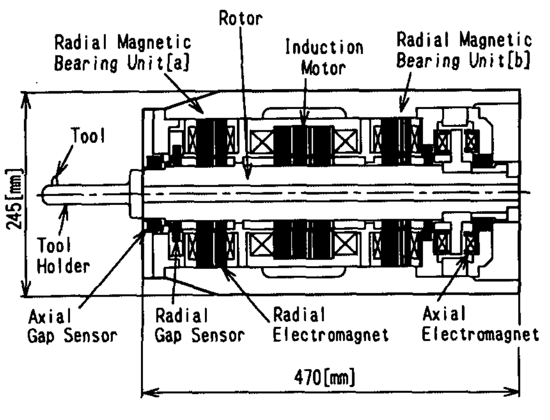


Fig.6 Cross Section of Magnetic Bearing Spindle
( Manufactured by Seiko Seiki Co., Ltd., Japan )

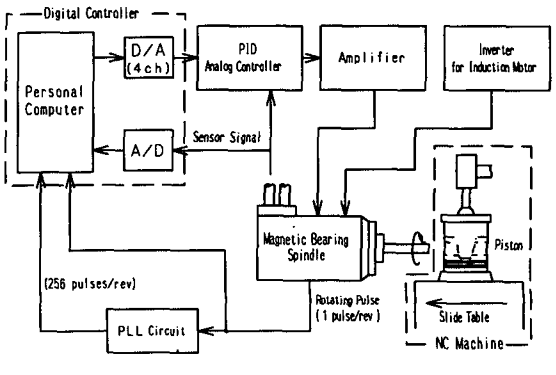


Fig.7 Block Diagram of Non-circular Fine Boring Machine

The rotation of magnetic bearing spindle is controlled by an induction motor. The position of the cutting tool is controlled by the magnetic bearings. The feed of a cross slide on which pistons are set up is controlled by a NC machine.

Input data for cutting tool positioning are successively and repeatedly put out to the magnetic bearing system from the personal computer through the four D/A converters. One bit of the D/A converters corresponds to 0.2[$\mu$ m] in positioning length. Input data are synchronized with 256 pulses per revolution, which are generated by dividing rotating pulse (one pulse per revolution) into 256 pulses using a PLL (Phase Locked Loop) circuit. Figure 8 shows a photograph of the non-circular fine boring machine.

## 5. Experiment

This section explains about the magnetic bearing spindle, the application of the PLC with ITFC for non-circular boring and cutting test.

### 5.1 Magnetic Bearing Spindle

Experiments were carried out using the magnetic bearing spindle (Fig.6), which is manufactured by Seiko Seiki Co., Ltd., Japan. The spindle consists of radial magnetic bearing unit[*a*], unit[*b*], axial electromagnet, rotor and gap sensors. The gap sensors are of the inductive type with a resolution of 1 [ $\mu$ m]. The displacement of the rotor is measured by using the change of the inductance of sensing coil in gap sensor.

### 5.2 Implementation of the PLC with ITFC

An engine piston was used as a workpiece for non-circular boring.

First is explained about the reference (desired) profile of piston pin bore and the calculation of the reference trajectory of rotor displacement. When the bore diameter is about 30[mm], bores with about 20 to 50[$\mu$ m] deviation from a circle are effective in reducing stress concentrated in the inner side of the piston pin bore (Izumi, 1995). We assume, therefore, the reference profile of piston pin bore to be

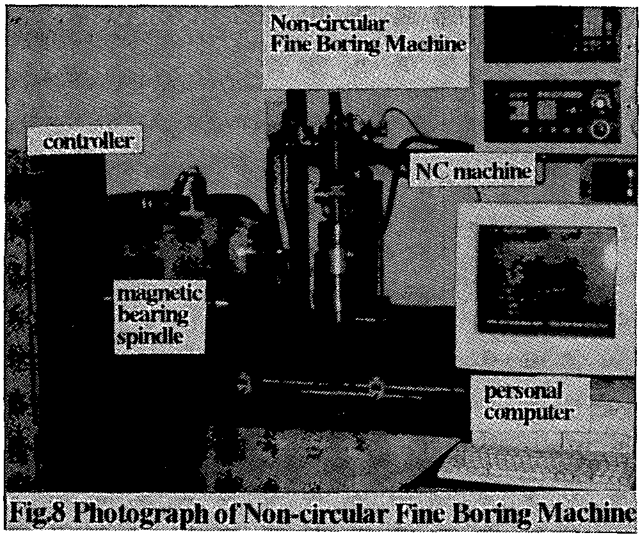


Fig.8 Photograph of Non-circular Fine Boring Machine

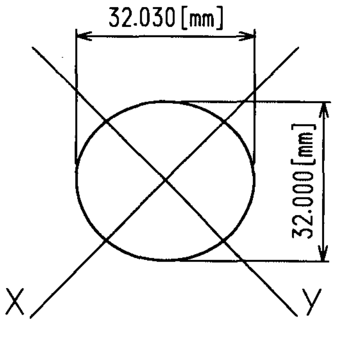


Fig.9 Reference Profile of the Hole
$\tilde{d}(\phi) = 7.5[\mu m] \cdot \cos(2\phi + 90^\circ)$
$|rc| = 16.0075[mm]$

$$\tilde{d}(\phi) = 7.5\ [\mu m] \cdot \cos(2\phi + 90^\circ) \tag{11}$$

(See Fig. 9.)

Using eq.(1), (6) and (7), the reference trajectory of rotor displacement is calculated. The calculated reference trajectories of rotor displacement are given by

$$\tilde{X}_a = 4.9\ [\mu m] \cdot \exp\{ j\,(-\omega t - 90^\circ)\} \tag{12}$$

$$\tilde{X}_b = 3.5\ [\mu m] \cdot \exp\{ j\,(-\omega t + 90^\circ)\} \tag{13}$$

Secondly the measurement of transfer function matrix is explained. Define the symbols used to explain a procedure of the PLC with ITFC as follows.

$n$ : repetitive number of the PLC

$R(t)$ : reference input

$x(t) = {}^{T}[x_a, y_a, x_b, y_b]$ : rotor displacement

$x^*(t) = {}^{T}[x_a, y_a, x_b, y_b]$ : component of $x$ with the same frequency as the rotor speed

$v(t) = {}^{T}[v_{xa}, v_{ya}, v_{xb}, v_{yb}]$ : compensatory input

${G^f_{pq}}^{-1}$: the inverse transfer matrix at f [Hz]. ($p,q$=1,2,3,4)

The transfer characteristic of magnetic bearing system at f [Hz] is described by the following equation.

$${}^{T}[x_a, y_a, x_b, y_b] = (G^f_{pq}) \cdot {}^{T}[v_{xa}, v_{ya}, v_{xb}, v_{yb}] \tag{14}$$

$$G^f_{pq} = A^f_{pq} \cdot \exp(j\phi^f_{pq}) \quad (p,q=1,2,3,4)$$

Each term of $x(t)$ is measured when a sinusoidal test signal is given to each term of $v(t)$. The measurement is carried out when the rotor is not rotating. This is reasonable because the rotor speed is low enough to assume negligible gyro effects. Table I shows the transfer function matrix measured by the experiment at 25[Hz]. The inverse transfer function matrix ${G^f_{pq}}^{-1}$ are calculated from the transfer function matrix $G^f_{pq}$ obtained by the experiment to implement the PLC with ITFC. Cutting tests are carried out at 25[Hz] because a beat was observed in the radial motions of the rotor above 25[Hz]. This beat is due to slight difference in rotation speed between the rotor and the electromagnetic field of the induction motor.

**TABLE I -TRANSFER FUNCTION MATRIX ($G^f_{pq}$) at $f$=25[Hz]**

$${}^{T}[x_a, y_a, x_b, y_b] = (G^f_{pq}) \cdot {}^{T}[v_{xa}, v_{ya}, v_{xb}, v_{yb}]$$

$$G^f_{pq} = A^f_{pq} \cdot \exp(j\phi^f_{pq})$$

| | $A^f_{pq}$ (amplitude [$\mu$m /v]) | | | | $\phi^f_{pq}$ (phase [deg]) | | | |
|---|---|---|---|---|---|---|---|---|
| p\q | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1 | 18.3 | ---- | 0.5 | ---- | -178 | ---- | -170 | ---- |
| 2 | ---- | 19.2 | ---- | 0.5 | ---- | -180 | ---- | -180 |
| 3 | 1.9 | ---- | 11.7 | ---- | -175 | ---- | -175 | ---- |
| 4 | ---- | 1.9 | ---- | 11.4 | ---- | -180 | ---- | -174 |

**---- : negligible because amplitude is small**

Finally, the procedure of the PLC with ITFC to realize the reference profile is as follows:

[n·1] Compensation with $v_n$ begins. $v_n$ is given to the controlled system through four D/A converters every rotating synchronous pulse.

[n·2] $x_n$ is sampled by the A/D converter every rotating synchronous pulse.

[n·3] $x^*_n$ is calculated by means of Fourier series expansion. [n·3] corresponds to $F(s)$ in Fig.4.

[n·4] $x^*_n$ is multiplied by $G^{f}_{pq}{}^{-1}$ from the left, where $G^{f}_{pq}{}^{-1}$ uses the above calculated result. [n·4] corresponds to $G^{-1}(s)$ in Fig.4.

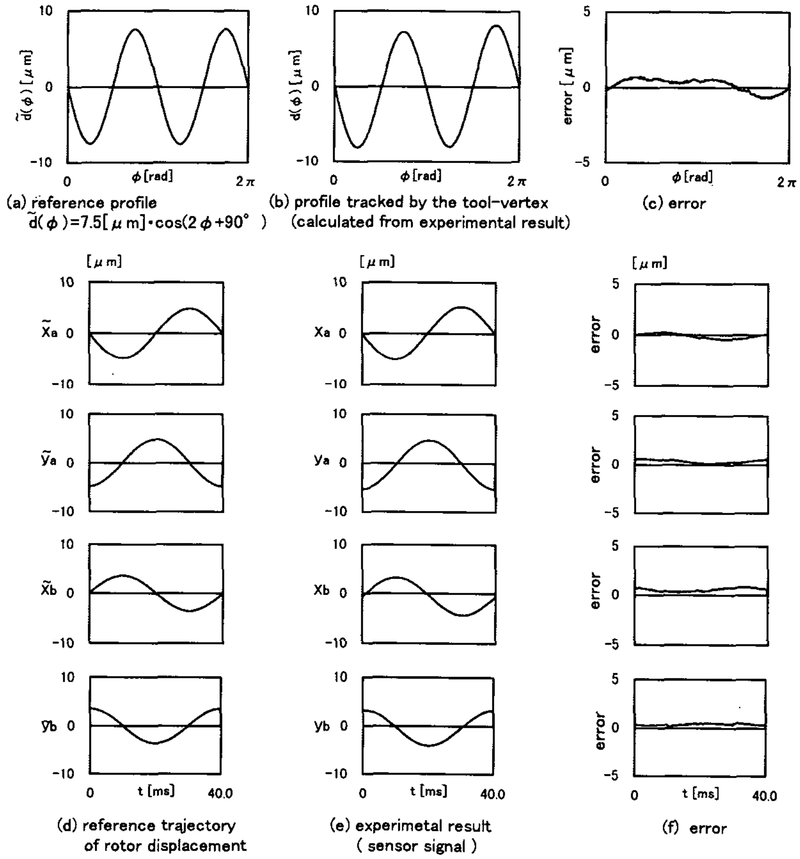
[n·5] The next compensatory input $v_{n+1}$ is calculated by the following equation:

$$v_{n+1} = \sum_{k=0}^{K} G^{f}_{pq}{}^{-1} \cdot (R - x^*_k) + v_n \tag{15}$$

The procedure of the PLC with ITFC is repeated until the errors $(R - x^*_k)$ converge to zero. The compensatory data is used when the errors approach to zero sufficiently.

## 5.3 Experimental Result of the PLC with ITFC

Figure 10 and 11 show the experimental results of the positioning of the rotor for non-circular boring respectively for the case of the compensatory input of repetitive number $n$=0, 2. Before implementations of PLC($n$=0), the reference profile does not coincide accurately with the profile calculated from experimental results.(See Fig.10) This implies that the estimation of $G^{f}_{pq}{}^{-1}$ has some errors. As shown in Fig.11, the error can be reduce by applying PLC with ITFC repeatedly.



(a) reference profile d̃(φ)=7.5[μm]·cos(2φ+90°)

(b) profile tracked by the tool-vertex (calculated from experimental result)

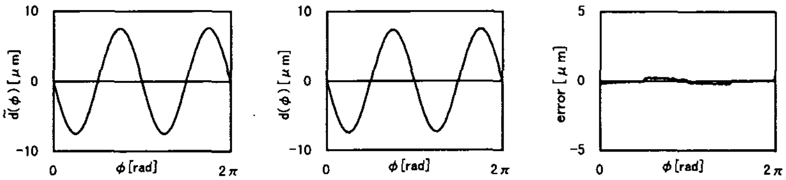
(c) error

(d) reference trajectory of rotor displacement

(e) experimetal result ( sensor signal )

(f) error

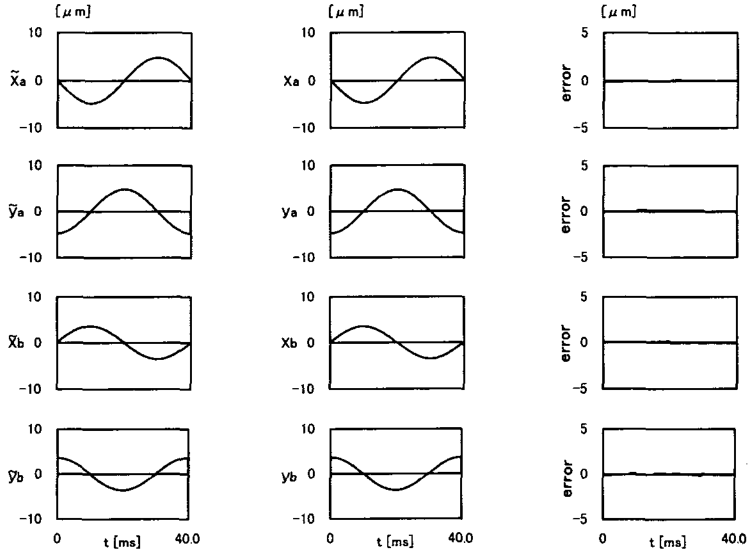
**Fig.10 Experimental Result of Positioning of the Rotor for Non-circular Boring ( repetitive number : n=0 )**



(a) reference profile
d̃(φ)=7.5[μ m]•cos(2φ+90°)

(b) profile tracked by the tool-vertex
(calculated from experimental result)

(c) error



(d) reference trajectory
of rotor displacement

(e) experimetal result
( sensor signal )

(f) error

**Fig.11 Experimental Result of Positioning of the Rotor for Non-circular Boring ( repetitive number : n=2 )**

### 5.4 Cutting Test

The compensatory input of the repetitive number $n$=2 was used during cutting test. Figure 12 shows the profile accuracy of cutting a piston pin bore. The profile of the piston pin bore is acquired by measuring the deviation from the reference circle. As shown in Fig.12, the difference between the reference profile and the cutting profile is within 2 [μ m].

## 6. Conclusions

In this research accurate non-circular fine boring was realized for piston pin bores by using a magnetic bearing spindle. The trajectory of rotor displacement was calculated by choosing the axis trajectory having a lower frequency component and minimizing control current on the magnetic coil. Experiments were carried out to demonstrate that the PLC with ITFC was effective for the piston pin bore application.

Several cutting tests were carried out for a non-circular piston pin bore at a rotational speed of 25[rps] (1,500[rpm]) using the developed boring machine. By applying the PLC with ITFC to non-circular piston pin boring, the target profile was realized within 2 [μ m].

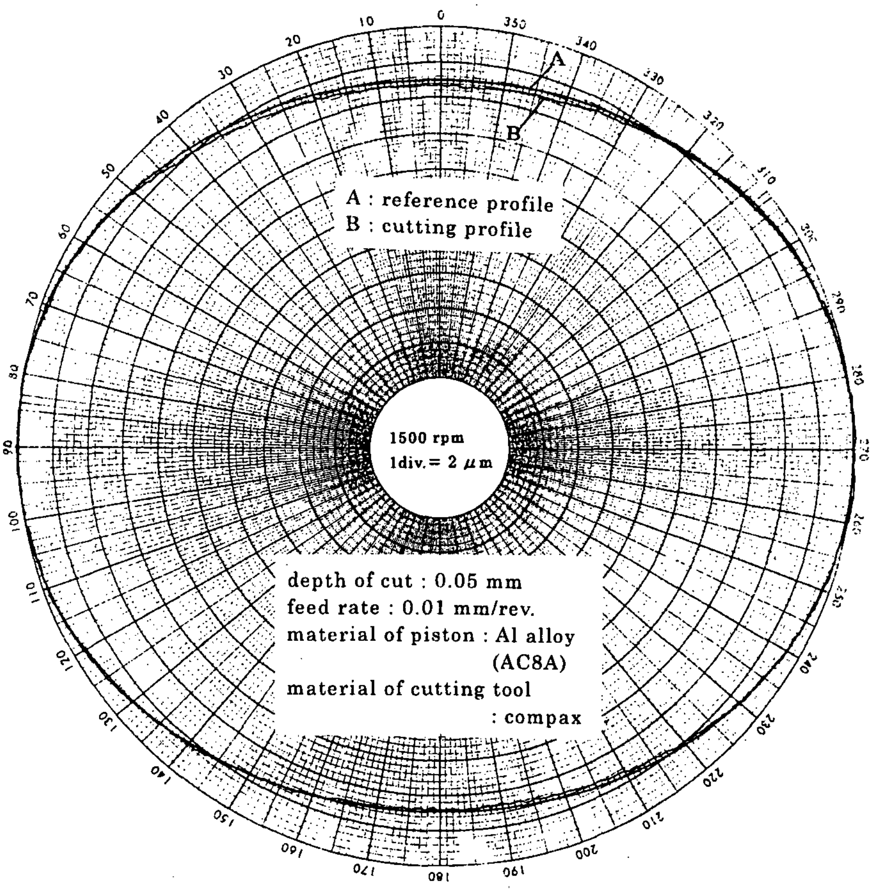


Fig.12 Profile Accuracy of Cutting Piston Pin Bore

**Acknowledgement**

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