The Influence of the Machining and Assembling Errors on the Performance of the Shaft Supported by Active Magnetic Bearings*

Dea-Gon KIM** and Kyung-Woong KIM**

AMB (Active Magnetic Bearing) system consists of sensors, controllers, power amplifiers, and electromagnets. If all the elements are ideal, the position of the shaft could be controlled up to the sensor resolution. Because each element in real system has mechanical and electrical losses and nonlinearities, it is impossible to attain the desired performance. So far in order to obtain the desired performance of the AMB system, an additional controller or filter has been used in conventional control algorithm. Other factors that may affect the shaft behavior are the machining errors due to the machine work, and the assembling errors due to the accumulated machining errors or asymmetric screw down. The purposes of this paper are to model the machining and assembling errors in the 5-axis controlled AMBs, and to show the influence of the machining and assembling errors on the performance of the shaft supported by AMBs. In view of the results so far achieved, the roundness error of the radial sensor target and the perpendicularity error of the thrust rotor have considerable influence on the rotational precision of the shaft, however the machining errors of the radial rotor and assembling errors of the radial stators have little influence on the rotational precision of the shaft. But when the magnitude of the assembling errors increases over a certain limit, the bearing can not support the shaft properly.

Key Words: AMB (Active Magnetic Bearing), Machining Errors, Assembling Errors

1. Introduction

AMB system consists of sensors, controllers, power amplifiers, and so on. Sensor detects the shaft position, and converted into the controlled signal. This signal is properly amplified and supplied to electromagnets.

If each element of the AMB system is ideal, theoretically it should be possible to control the shaft position to the sensor resolution. But it is impossible to control up to the desired position because of the nonlinearities and losses of the electric and magnetic components. These nonlinearities and losses might influence on the performance of the AMBs and the rotational precision of the shaft. Many studies for the improvement of these problems have been performed, e.g. the selection of the proper magnetic material, the

improvement of the control algorithm, the minimization of the electric and magnetic losses, and so on^{(1),(2)}.

Another possibility to have an undesired performance of the AMB system are the machining errors caused by the machine work or the electric and magnetic runout. Johnson, et al.⁽³⁾ reported that the notch filter in the lead-lag compensator removed roundness error on the surface of the radial sensor target. Kim, et al.⁽⁴⁾ proposed that the runout identification scheme using the extended influence coefficient method could eliminate runout effectively. Up to now to obtain better rotational precision of the shaft, an additional controller has been used to produce more high control signal or to reject the frequency component which affect on the rotational precision.

The higher precision elements require the higher manufacturing cost and effort. In the AMB system each mechanical element is machined by the proper materials which can minimize the flux leakage and loss, and then assembles to the shaft. In the finished

* Received 25th February, 1997

** Department of Mechanical Engineering, KAIST, 373-1 Kusong-dong Yousong-gu Taejeon 305-701, Korea

products, the machining and assembling errors are developed according to the machinery and the condition of the machine work, and which cause an effect on the sensor signal or create an irregular air gap. Finally, it is impossible to attain the desired electromagnetic force. However, because there are few studies on the allowable errors for the desired performance of the AMB system, machinery and machine tools have been selected according to the experience of the designer. For this reason some element machined over precisely may increase the manufacturing cost or rise the magnetic losses, while roughly machined element may influence on the rotational precision of the shaft.

The purposes of this paper are to model the machining and assembling errors that may appear in the 5-axis controlled AMBs, and to show the influence of the machining and assembling errors on the performance of the shaft by the analysis of the system considered these errors.

Nomenclature

A	: pole face area
b_i	: bearing length
d_{rci}	: cylindricity error of the radial rotor
d_{rfi}	: roundness error of the radial rotor
d_{Rpi}	: parallelity error of the radial stator
d_{Rqi}	: coaxiality error of the radial stator
d_{sfi}	: roundness error of the radial sensor target
d_{td}	: perpendicularity error of the thrust rotor
d_{tfi}	: roundness error on the surface of the thrust rotor
d_{Tai}	: assembling error of the thrust stator
l	: bearing span
m	: mass
n_{rfi}	: lobe number of the roundness error of the radial rotor
n_{sfi}	: lobe number of the roundness error of the radial rotor
μ_0	: permeability of the free space
Subscript	
a	: assembling error
c	: cylindricity error
d	: perpendicularity error
f	: roundness error
i	: classification of radial bearing
m	: machining error
p	: parallelity error
q	: coaxiality error
r	: radial rotor
s	: radial sensor target
R	: radial stator
t	: thrust rotor
T	: thrust stator

2. Control of the AMB System

2.1 Electromagnetic force

As current flows in the coil, the magnetic field should be formed perpendicular to the current. Then the attraction force is generated at the boundaries between differing permeability. This force calls reluctance force distinguished from Lorenz force, and depends on the permeability of the material. From the principle of virtual work, it is possible to derive the force acting on the shaft.

$$f = \frac{\mu_0 N^2 i^2 A}{h^2} \quad (1)$$

Equation (1) shows the quadratic dependence on the current and inversely quadratic dependence on the air gap. Generally it is simplified through the linearization method as the Taylor expansion and then applies the theory or control algorithm. In this study it is assumed that the magnetic flux density is distributed constantly on the pole face and there are no losses. From these assumptions the nonlinear equation (1) is modified to the equation acting on the infinitesimal area, and then force considered the machining and manufacturing errors can be obtained by integration of the whole area.

In arbitrary angle α the magnetic force generated on the infinitesimal area is modified as follows.

$$df = \frac{\mu_0 N^2 i^2 dA}{h^2} \quad (2)$$

2.2 The equations of the motion

Figure 1 shows the schematics of the AMB system. It is assumed that the shaft is rigid and the displacement is small. The small motions of the shaft can be displayed by the displacements x , y , z of its center of mass and the inclination angle θ_y , θ_x about the x and y axis.

The equations of motions are:

$$\begin{aligned} m\ddot{z} &= f_z \\ m\ddot{x} &= f_{x1} + f_{x2} \\ m\ddot{y} &= f_{y1} + f_{y2} \\ j_d \ddot{\theta}_x &= f_{y1} l_1 - f_{y2} l_2 + m_x + j_p \omega \dot{\theta}_y \\ j_d \ddot{\theta}_y &= -f_{x1} l_1 + f_{x2} l_2 + m_y - j_p \omega \dot{\theta}_x \end{aligned} \quad (3)$$

where f_z , f_{x1} , f_{x2} , f_{y1} , f_{y2} represent the magnetic force acting on each direction, and m_x and m_y represent the x and y directional moments due to the asymmetric force of the axial direction.

Because the infinitesimal area is $dA = r_r da dz_i$ for the radial magnetic bearing, Eq. (2) is described as follows:

$$f_q = \int \frac{\mu_0 N_{ri}^2 i_{ri}^2 r_r}{h_{ri}^2} da_i dz_i \quad (4)$$

And for the thrust magnetic bearing the infinitesimal area is $dA = r da dr$, it also described as follows:

Fig. 1 AMBs assembly

$$f_z = \int \mu_0 N_i^2 r \left(\frac{i_{i2}^2}{h_{i2}^2} - \frac{i_{i1}^2}{h_{i1}^2} \right) da dr \quad (5)$$

$$\begin{bmatrix} m_x \\ m_y \end{bmatrix} = \int \mu_0 N_i^2 r^2 \begin{bmatrix} \sin \alpha \\ -\cos \alpha \end{bmatrix} \left(\frac{i_{i2}^2}{h_{i2}^2} - \frac{i_{i1}^2}{h_{i1}^2} \right) da dr \quad (6)$$

There is relation between the displacement of the shaft at the mass center and at each bearing center for the small motions of the shaft.

$$\begin{aligned} x_1 &= x - l_1 \theta_x \\ x_2 &= x + l_2 \theta_x \\ y_1 &= y + l_1 \theta_y \\ y_2 &= y - l_2 \theta_y \end{aligned} \quad (7)$$

By substituting Eq. (7) for Eq. (3) we can obtain the equations of motion for the coordination of each bearing.

$$m\ddot{q} + g\dot{q} = f + f_u + f_e \quad (8)$$

$$q = \{z \ x_1 \ x_2 \ y_1 \ y_2\}^T \quad (9)$$

$$m = \frac{1}{l^2} \begin{bmatrix} m & 0 & 0 & 0 & 0 \\ 0 & ml_1^2 + j_d & ml_1 l_2 - j_d & 0 & 0 \\ 0 & ml_1 l_2 - j_d & ml_2^2 + j_d & 0 & 0 \\ 0 & 0 & 0 & ml_1^2 + j_d & 0 \\ 0 & 0 & 0 & 0 & ml_2^2 + j_d \end{bmatrix} \quad (10)$$

$$g = \frac{j_p \omega}{l^2} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & -1 & 1 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \end{bmatrix} \quad (11)$$

$$f = \left\{ f_z \ f_{x1} - \frac{m_y}{l} \ f_{x2} + \frac{m_y}{l} \ f_{y1} + \frac{m_y}{l} \ f_{y2} - \frac{m_x}{l} \right\}^T \quad (12)$$

Fig. 2 Block diagram

$$f_u = m\omega^2 \begin{bmatrix} 0 \\ e_1 \cos(\omega t + \zeta_0) \\ e_2 \cos(\omega t + \xi_0) \\ e_1 \sin(\omega t + \zeta_0) \\ e_2 \sin(\omega t + \xi_0) \end{bmatrix} \quad (13)$$

$$f_e = \{f_{ez} \ f_{ex1} \ f_{ex2} \ f_{ey1} \ f_{ey2}\}^T \quad (14)$$

2.3 Control circuit

Figure 2 shows that the block diagram of the AMB system. Generally each element has an undesired losses and nonlinearities, and may influence on the performance of the magnetic bearing. However in this study we assumed that there are no losses or nonlinearities at each element. In this study PID controller is modelled because of the wide use.

3. Modelling of the Machining and Assembling Errors

The mechanical elements which need machine work in the 4-axis controlled magnetic bearing system are roughly divided into the shaft, radial stators, and housing to fix stators. Each element is machined of the proper materials which can minimize the flux leakage and loss, and then assembles to the shaft. As shown in Fig. 1, shaft consists of the radial and thrust rotor which forms the magnetic flux, and the sensor target.

Generally radial bearing is made of the laminated

silicon-steel to reduce the eddy current loss, while in the thrust bearing mild steel is used because the eddy current loss of the thrust bearing is less than that of the radial bearing. And it is designed for ease to assemble and disassemble into a housing according to the condition of the system.

3.1 Machining and assembling errors of the radial bearings

In the radial magnetic bearing the machining and assembling errors, which might influence the shaft behavior, appears on the surface of the radial rotor, the radial stator, and the radial sensor target. If there are machining errors or assembling errors at the radial bearing, it is impossible to attain the desired magnetic force because of the irregular airgap on the radial and axial direction. And if there are machining errors on the surface of the radial sensor target, it is impossible to attain the desired magnetic force because the sensor detects the displacement of the shaft with the machining errors.

3.1.1 Airgap of the radial bearing at arbitrary position Figure 3 represents the airgap between the radial stator and the radial rotor in the arbitrary position (z_i, α_i) , having the machining errors on each surface of the stator and rotor.

For the eccentricity OC, the airgap between the stator and the rotor in the arbitrary position (z_i, α_i) is as follows:

$$h_{ri} = h_{rs} - x_{zi} \cos \alpha_i - y_{zi} \sin \alpha_i + h_{rmi} + h_{Rmi} \quad (15)$$

x_{zi} and y_{zi} are the distances from the geometric center of the stator to the geometric center of the rotor at the arbitrary position (z_i, α_i) , h_{rmi} is the machining errors on the surface of the radial rotor, and h_{Rmi} is the machining errors on the surface of the radial stator.

3.1.2 The machining errors of the radial rotor

There are two ways of examining the machining errors of the radial rotor, one is the roundness error on the radial direction and the other is the cylindricity error on the axial direction. Roundness error can be expressed by the summation of the various sinusoidal func-

Fig. 3 Air gap of the radial magnetic bearing

tions, however in this study it is modelled having only one frequency component. And to see the maximum effect of the roundness error, it is assumed that the roundness error is constantly distributed in axial direction. The cylindricity error also can be represented by the summation of the various sinusoidal function, however to see the maximum effect of the cylindricity error it is modelled after the type of the taper.

Figure 4(a) shows the roundness error of the radial rotor constituting only one frequency component, and (b) shows the cylindricity error of the taper type.

$$h_{rmi} = \frac{d_{rfi}}{2} \sin(n_{rfi} \alpha_i - n_{rfi} \omega t + \phi_{rfi}) + d_{rci} \frac{z_i - z_{i0}}{b_i} \quad (16)$$

3.1.3 The machining errors of the radial sensor target

If there are machining errors on the surface of the radial sensor target, sensor detects the displacement of the shaft with the machining errors at its point, hence it is impossible to levitate the shaft to the desired position.

For the convenient analysis, we assume that the sensor detects the shaft position at one point. If there is a roundness error on the surface of the radial sensor target as in Fig. 4(a), each directional sensor detects the displacement including the roundness error.

$$x_{smi} = \frac{d_{sfi}}{2} \sin(n_{sfi} \omega t + \phi_{sfi}) \quad (17)$$

$$y_{smi} = \frac{d_{sfi}}{2} \cos(n_{sfi} \omega t + \phi_{sfi})$$

3.1.4 The assembling errors of the radial stators

The radial stators, which are similar to the radial rotor, have roundness errors as well as cylindricity errors at pole face, but it is not considered the machining errors on the surface of the radial stator because

Fig. 4 Machining errors on the shaft surface

it might little effect on the shaft rotation. However if there are machining errors on the conjoining surface with the housing or the irregularly screw down, there must be the misalignment between the center lines of each radial stator.

Figure 5 shows the assembling error of the radial stators. If the radial stators are assembled having the coaxiality error d_{Rq} and the parallelity error d_{Rpi} as in Fig. 5, the distance between the center line of the stator and the rotor in the arbitrary axial position z_i is as follows.

$$x_{Rqi} = d_{Rq} \frac{z_i}{l} \cos \psi_{Rq} \quad (18)$$

$$y_{Rqi} = d_{Rq} \frac{z_i}{l} \sin \psi_{Rq}$$

$$x_{Rpi} = z_i \tan -\eta_{Rpyi} + r_R \left(1 - \frac{1}{\cos -\eta_{Rpyi}} \right) \quad (19)$$

$$y_{Rpi} = z_i \tan \eta_{Rpxi} + r_R \left(1 - \frac{1}{\cos -\eta_{Rpxi}} \right)$$

Where, $\tan \eta_{Rpxi} = d_{Rpi} / 2r_R \cos \psi_{Rpi}$, and $\tan -\eta_{Rpyi} = d_{Rpi} / 2r_R \sin \psi_{Rpi}$

3.1.5 The distance between the center line of the radial stator and rotor The small motion of the shaft represents the sum of the translational displacement and the conical displacement. If the radial stator has assembling errors as Eqs.(18) and (19), the distance between the center line of the radial stator and rotor, in the arbitrary axial position z_i , is the sum of the translational displacement at the geometric center of the stator, the conical displacement, and the distance due to the assembling errors of the radial stators.

Fig. 5 Assembling errors of the radial stator

$$\begin{aligned} x_{z1} &= x_1 - \frac{z_1}{l} (x_1 - x_2) - x_{Rq1} + x_{Rpi1} \\ x_{z2} &= x_2 - \frac{z_2}{l} (x_1 - x_2) - x_{Rq2} + x_{Rpi2} \\ y_{z1} &= y_1 - \frac{z_1}{l} (y_1 - y_2) - y_{Rq1} + y_{Rpi1} \\ y_{z2} &= y_2 - \frac{z_2}{l} (y_1 - y_2) - y_{Rq2} + y_{Rpi2} \end{aligned} \quad (20)$$

3.2 Machining and assembling errors of the thrust bearings

The machining and assembling errors of the thrust bearings also appear on the surface of the thrust rotor and the thrust stator. Similar to the radial bearing, the machining errors of the thrust rotor and the assembling errors of the stator should effect the air gap, and it is also impossible to attain the desired magnetic force. However because the thrust sensor fixes on the geometric center line of the shaft in general, the machining errors of the thrust sensor target is not considered.

3.2.1 The air gap of the thrust bearing in the arbitrary position Figure 6 (a) describes the z directional gap in the arbitrary position (r, a) when the plate is declined to small angle ζ . If angles ζ_x and ζ_y are the x and y directional component of the angle between the $x-y$ plane and the plate, it can be described that the distance between the $x-y$ plane and the plate at position (r, a) is as follows.

$$z_\zeta = r \sin a \cos(\zeta_x) + r \cos a \sin(-\zeta_y) \quad (21)$$

Figure 6 (b) shows the air gap between the thrust stator and thrust rotor in the arbitrary position (r, a). The air gap is presented by the displacement of the translational motion of the shaft z , the displacement of the conical motion of the shaft z_c , the distance change due to the machining errors of the surface of the stators z_{Tmi} and rotor z_{tmi} , and the distance change due to the assembling errors of the stators z_{Tai} .

$$\begin{aligned} h_{t1} &= h_{ts} + z + z_c + z_{tm1} - z_{Tm1} - z_{Ta1} \\ h_{t2} &= h_{ts} - z - z_c - z_{tm2} + z_{Tm2} + z_{Ta2} \end{aligned} \quad (22)$$

3.2.2 The displacement of the conical motion of the shaft For the conical motion of the shaft air

Fig. 6 Air gap of the thrust bearing

gap will be changed as in Fig. 6, and substituting the angle ζ_x and ζ_y for the angle θ_x and θ_y , the change of the air gap is as follows.

$$z_t = r \sin \alpha \tan(\theta_x) + r \cos \alpha \tan(-\theta_y) \quad (23)$$

3.2.3 The machining errors of the thrust rotor

At the arbitrary moment, if the thrust rotor declined having the perpendicularity errors ζ_{td} to the $x-y$ plane as Fig. 6, the air gap between the $x-y$ plane and the thrust rotor must be changed as shown below.

$$z_{td} = \frac{d_{td}r}{2r_t} \cos(\alpha - \omega t - \psi_{td}) \quad (24)$$

Similarly if the surface of the thrust rotor has the roundness error, the distance between the stator and the rotor also changes as follows.

$$z_{tfi} = \frac{d_{tfi}r}{2r_t} \cos(n_{tfi}\alpha - n_{tfi}\omega t - \psi_{td}) \quad (25)$$

Consequently, the air gap between the thrust stators and the thrust rotor at the point (r, α) are the sum of the two Eqs.(24) and (25).

$$z_{tm1} = z_{td} + z_{tfi1} \quad (26)$$

$$z_{tm2} = z_{td} - z_{tfi2}$$

3.2.4 The machining and assembling errors of the thrust stators The pole face of the thrust stators also have the machining errors, but it is not considered that the machining errors on the pole face of the thrust stators might little effect on the shaft rotation. However if there are machining errors on the conjoining surface with the housing or the irregularly screw down, there must be the misalignment between the center lines of each radial stator as in Fig. 6.

$$z_{Tai} = \frac{d_{Tai}r}{2r_t} \cos(\alpha - \psi_{Tai}) \quad (27)$$

4. Simulation Result

Initial position of the shaft is detected by the sensor, which converted into the controlled current by PID-controller and current feedback circuit containing power amplifier and electromagnet. After which it is substituted by this controlled current for the Eqs. (4)-(6), we can obtain the electromagnetic force in each direction. And to substitute for the Eq.(8), the instantaneous equations of the motion at time t can be obtained. The ordinary linear differential equations can be solved by the numerical analysis as Euler method, Runge-Kutta method, and so on. In this study the equations of the motion are solved by using the 4th order Runge-Kutta method. By repeating the above process using each step displacement, we can obtain the next step displacement of the shaft.

The specification of the AMB system used this simulation is shown Table 1. Sensor gain is selected as follows; 1.3 for proportional gain, 0.005 for derivative gain, and 10 for integral gain.

Table 1 Specification

pole face area	9.6 × 10 mm ²
air gap	0.5 mm
coil turn	300 turns
half pole angle	22 °
bearing length	10 mm
diameter of the shaft	30 mm
diameter of the rotor	60 mm
mass	1.89 kg
sensor gain	5000 V/m
current/voltage gain of the power amplifier	0.96 A/V
time constant of the power amplifier	0.0014 s
y-dir. bias current	upper: 0.55 A lower: 0.25 A
x-dir. bias current	0.4 A

Fig. 7 Running amplitude for the case of the roundness error on the surface of the radial rotor

Fig. 8 Running amplitude for the case of the cylindricity error of the radial rotor

Figures 7 - 8 represent the simulation in the case of the machining errors on the surface of the radial rotor. Figure 7 shows the running amplitude of the shaft with the lobe number of the roundness error. In the case of an even lobe number, it has little influence on the shaft behavior, due to the symmetric shape of the shaft about z -axis. Figure 8 shows the running amplitude of the shaft with the cylindricity error on the surface of the radial rotor. Though the cylindricity error of the radial rotor has influence on the performance of the shaft, its effect is negligible in comparison with the magnitude of the cylindricity

error. But if the magnitude is beyond any limitation, shaft will be bumped into the stator. However in real system the cylindricity error of the radial rotor is small to compare with the value using above simulation.

Figures 9 - 10 represent the simulation results in the case of the roundness error on the surface of the radial sensor target. However it is not considered the mass eccentricity, another peak due to the roundness error is shown in Fig. 9. Figure 10 is the lissajous of the shaft with the lobe number of the roundness error, and shows the combined orbit of the mass eccentricity and roundness error. From these results it can be seen that the machining error of the radial sensor target has important influence on the shaft behavior.

Figure 11 shows the lissajous of the shaft in the case of the perpendicularity error of the thrust rotor ($d_{tr}=2\mu m$), which has influence on the shaft behavior. However the waviness error of the thrust rotor

Fig. 9 Running amplitude for the case of the roundness error on the surface of the radial sensor target

Fig. 10 Lissajous in the case of the roundness error of the radial sensor target ($N=4\,000$ rpm, $e_1=e_2=1\mu m$, $d_{sr1}=0$, $d_{sr2}=2\mu m$)

as Eq.(25) has little influence on the shaft behavior.

According to this simulation, the assembling errors of the radial stators and the thrust stators have little influence on the magnitude of the lissajous of the shaft. But if it is beyond any limitation of the assembling errors, the AMBs can not support the shaft. Figure 12 shows the maximum assembling errors of the radial stators which can support the shaft properly. Figure 13 represents the limitation of the assembling error of the thrust stators. Figure 13(a) shows that the only left thrust stator reveals the assembling errors as in Fig. 6(b), and Fig. 13(b) shows that the left and right thrust stators have the same magnitude of the assembling errors. Because the asymmetric force of the axial direction in case (b) is bigger than (a), the working limitation in case (b) is lower than

Fig. 11 Running amplitude for the case of the perpendicularity error of the thrust rotor

Fig. 12 Limitation of the assembling error for the radial stator

Fig. 13 Limitation of the assembling error for the thrust stator

in case (a).

Generally the AMBs should be operated over system resonance, the system resonance used in this simulation is about 10 000 rpm. In order to investigate the effect of the machining and assembling errors at high rotational speed we define the remaining extent of the effect of the machining and assembling errors as $[\text{maximum lissajous at 50 000 rpm}] / [\text{magnitude of the machining or assembling error}] \times 100 [\%]$. Table 2 shows the results of this remaining effect of the machining and assembling errors at 50 000 rpm. In this examination we can see that the influence of the machining and assembling errors except for the roundness error on the radial sensor target and the perpendicularity error of the thrust rotor are diminished as increasement of the shaft velocity.

5. Conclusion

This paper is to model the machining and assembling errors in the 5-axis controlled AMBs using the PID control algorithm, and to show the influence of the machining and assembling errors on the performance of the shaft supported by AMBs by the analysis of the system.

For the convenience of the analysis, it is assumed that the magnetic losses is neglected, the magnetic flux density of the surface of the pole face is constantly distributed, nonlinearity of each element of the

Table 2 The effect of the machining and assembling errors at 50 000 rpm

machining and assembling errors		maximum lissajous magnitude of the errors $\times 100 [\%]$
radial rotor	roundness error	$\frac{A}{d_{rt}} \times 100 \approx 0.001 [\%]$
	cylindricity error	$\frac{A}{d_{rc}} \times 100 \approx 0.002 [\%]$
radial sensor target	roundness error	$\frac{A}{d_{rt}} \times 100 \approx 75 [\%]$
thrust rotor	perpendicularity error	$\frac{A}{d_{td}} \times 100 \approx 70 [\%]$
	waviness error	$\frac{A}{d_{td}} \times 100 \approx 0.0001 [\%]$
stator	assembling error	$\frac{A}{d_{Ra}} \times 100 \approx \frac{A}{d_{Ta}} \times 100 \approx 0.0001 [\%]$

control circuit is neglected, and the sensor detects the displacement of the shaft at one point.

From the analysis it is concluded as follows.

(1) The machining errors of the radial rotor have little influence on the shaft behavior. Consequently there is no need to work the surface finishing which might increase the eddy current loss due to imperfect insulation between laminates.

(2) The roundness error on the surface of the radial sensor target and the perpendicularity error of the thrust rotor have considerable influence on the shaft behavior, and their effects do not vanished at high rotational speed. Because in high rotational speed these machining errors must be influenced on the rotational accuracy as well as mass eccentricity, it need to design and decide the condition of machine work and machinery considered these effects.

(3) However the assembling errors of the radial and thrust stators have little influence on the shaft behavior, but if it is increase over a certain limit, it can not perform as the bearing.

References

- (1) Higuchi, T. and Mizuno, T., Balancing Measurement System Using Magnetic Bearings, 1st Int'l Symp. on Magnetic Bearings, Switzerland, June 6-8, 1988, p. 327-334
- (2) Toumi, K.Y. and Ito, O., Dynamic Analysis and Control of High Speed and High Precision Active Magnetic Bearings, Trans. ASME, Journal of Dynamic Systems, Measurement, and Control, Vol. 114, (1992), p. 623-633.
- (3) Johnson, B.G. and Hockney, R.L., Active Synchronous Response Control of Rigid-Body Rotors, IMechE, 1988, C 290/88, p. 33-39.
- (4) Lee, C.W., Ha, Y.H., Joh, C.H. and Kim, C.H., In-Situ Identification of Active Magnetic Bearing System Using Directional Frequency Response Functions, Trans. ASME, Journal of Dynamic System, Measurement and Control, Vol. 118 (1996), p. 586-592.