HOW STATIC PRECISION OF AN AMB ROTOR SYSTEM IS AFFECTED BY HEATING OF THE THRUST DISK

Chen Liqun
Northwestern Polytechnical University, Xi'an, Shaanxi, P.R. China, chenliqu@public.xa.sn.cn
Shen Yunwen
Northwestern Polytechnical University, Xi'an, Shannxi, P.R. China
Yu Lie
Xi'an Jiaotong University, Xi'an, Shaanxi, P.R. China

ABSTRACT

Structural designs of thrust bearings, using both actual system working condition as well as experimental results in expander applications, were used to analyzed how the static precision of an AMB rotor system affected is affected by two variables – the temperature of environment and heating of thrust disk. A model for temperature distribution of the rotor was formulated. System static precision affected by rotor expansion and sensor temperature drift was analyzed in detail.

INTRODUCTION

The two most important differences in the characteristics of AMB applications in an expander are greater loads on thrust bearings than radial bearings and large temperature gradient distribution from the compressor side to the expander side of rotor. The thrust bearing is not only the largest part but also the largest heating source in the AMB system. System performance is obviously affected by rotor expansion and sensor temperature drift with temperature changes of the thrust bearing and the environment. So the thrust bearing plays a very important role in the AMB applications of the expander [1].

To minimize of iron losses, laminated configuration is introduced in most radial bearings. But thrust bearings are usually made of solid iron because of strength and manufacturing problems. When the thrust bearing is worked under large loads and high rotation speed, the heating caused by iron losses is much more than that in radial ones. Therefore, the thrust bearing is the main heating source in an AMB system in the expander application [2].

It is complex and difficult to describe the change of thrust bearing temperature and its influence on precision of AMB rotor system accurately. According to the structure design of the thrust bearing under actual system working conditions and experimental results, most components of the system worked well under good environment or controlled conditions. Some special technologies of sensors and actuators were used to avoid some of the control problems [3][4].

It is difficult to control the temperature of the rotor under high rotation speed such that a large gradient is distributed from the compressor side to the expander side of rotor. The rotor expansion and sensors near the rotor become main factors affecting the system precision. A linear model of rotor temperature distribution in the expander was formulated. How the static precision of the AMB rotor system was affected by rotor expansion and sensor temperature drift was analyzed. Some ways to avoid the precision problems are suggested at the end of this paper.

TEMPERATURE AFFECT ON SYSTEM

Rotor Expansion

The relationship between rotor expansion and temperature variation in radial and axial direction is

$$\begin{cases} \Delta L = L \cdot \alpha \cdot \Delta t \\ \Delta D = D \cdot \alpha \cdot \Delta t \end{cases}$$

Assuming small perturbation and ideal sensors, the rotor dimension change can be converted to the static disturbance of system output measurement.

System Frame Layout

Three schemes often used in an actual system are shown in Fig. 1.

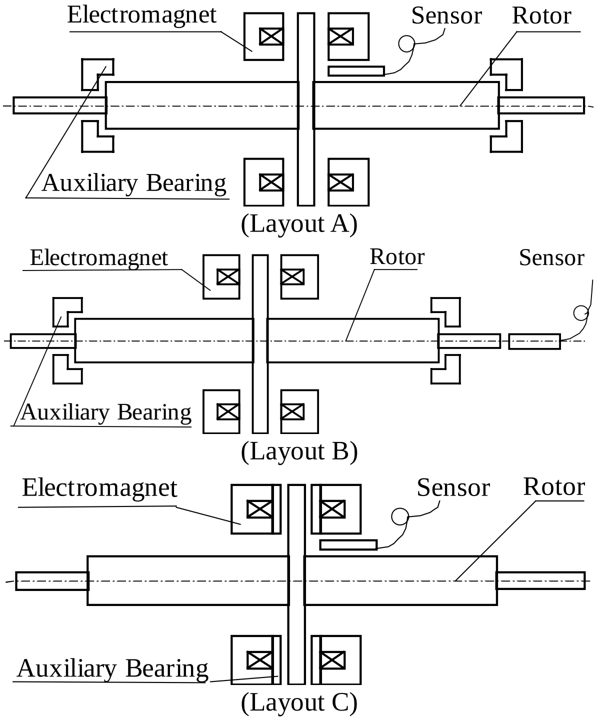

Fig. 1: Three Kinds of System Frame Layout

Temperature Distribution

Under steady working conditions of the expander, the temperature distribution is static. Assuming that the distribution is uniform along the circumferential direction and is linear along the axial direction, the equation of temperature distribution along these axes is written by

$$t = \begin{cases} T_t - \dfrac{T_t - T_c}{L_a} z & L_a \le z \le 0 \\ T_t + \dfrac{T_h - T_t}{L_b} z & 0 < z \le L_b \end{cases}$$

When the rotor temperature of the cold side, warm side and disk are known, the distribution curve is shown in Fig 2.

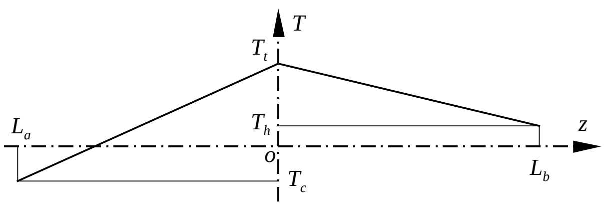

Fig. 2: Rotor Temperature Distribution Curve

Expansion Affect on Precision

Considering the expansion in differential length along the axial direction of the rotor, there is

$$dl = \alpha \cdot \Delta T \cdot dz = \alpha \cdot (T - T_0) \cdot dz$$
$$= \begin{cases} \alpha\left(T_t - T_0 - \dfrac{T_t - T_c}{L_a} z\right) dz & 0 \ge z \ge L_a \\ \alpha\left(T_t - T_0 + \dfrac{T_h - T_t}{L_b} z\right) dz & 0 < z \le L_b \end{cases}$$

The total expansion is

$$\Delta L = \int dl = \begin{cases} \alpha\left[(T_t - T_0)z - \dfrac{(T_t - T_c)z^2}{2L_a}\right] & L_a \le z \le 0 \\ \alpha\left[(T_t - T_0)z + \dfrac{(T_h - T_t)z^2}{2L_b}\right] & 0 < z \le L_b \end{cases}$$

Thrust Bearing

For layout A, only the gaps between the rotor and the auxiliary bearings can be changed by rotor expansion. When the rotor comes into contact with either side of the auxiliary bearing, the conditional equation is

$$|C_{at}| = \max\{|\Delta L_l|, |\Delta L_r|\}$$

Expansion curves under different disk temperatures and the contact temperature are shown in Fig. 3 and Table 1 respectively.

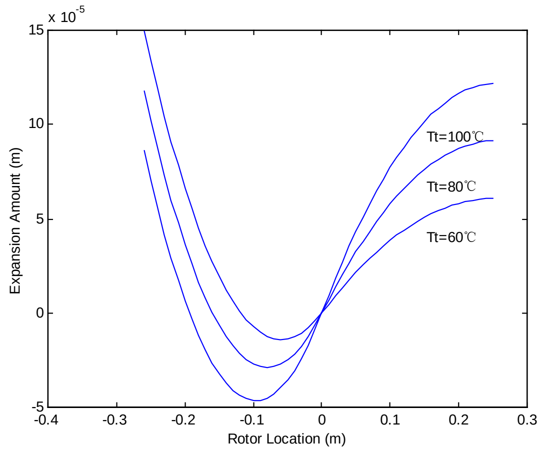

Fig 3: Expansion Curve

Table 1: Expansion and Contact Temperature (Layout A)

	T_t =60℃	T_t =80℃	T_t =100℃	T_t =120℃
ΔL_l	23.15e-6m	-3.22e-6m	-29.58e-6m	-55.94e-6m
ΔL_r	51.69e-6m	77.55e-6m	103.4e-6m	129.3e-6m
T_{tc}	97℃ (Right Auxiliary Bearing)			

For layout B, the thrust disk will be moved by the system control loop when expansion occurs. Imbalance currents in the electromagnet will be produced at the same time. The balance equations are given by

$$\begin{cases} C_{at} = -\Delta L_l + \Delta L_r \\ K_A \dfrac{(I_{A0} - \Delta i)^2}{(C_0 - \Delta L_r)^2} = K_B \dfrac{(I_{B0} + \Delta i)^2}{(C_0 + \Delta L_r)^2} \end{cases}$$

Calculation of the result of expansion, imbalance currents under different temperatures, and the contact temperature for layout B are shown in Table 2.

Table 2: Expansion, Imbalance Current and Contact Temperature (Layout B)

	T_t=60℃	T_t=80℃	T_t=100℃	T_t=120℃
ΔL_l	23.15e-6m	-3.22e-6m	-29.58e-6m	-55.94e-6m
ΔL_r	60.96e-6m	91.44e-6m	121.9e-6m	152.4e-6m
ΔL	-37.82e-6m	-94.66e-6m	-151.5e-6m	-208.3e-6m
Δi	1.2192A	1.8288A	2.4384A	3.0480A
T_{tc}	82℃ (Left Auxiliary Bearing)			

For layout C, because of the small dimension of the disk in the axial direction, the expansion effect on the system can be ignored.

Radial Bearing

In the radial bearings, the variation of the rotor diameter and the drift of the geometry center are mainly affected by rotor expansion. The location of radial bearings, auxiliary bearings, rotor, and sensors is shown in Fig. 4. The expansion of the radial bearings can be calculated by

$$\Delta D(z) = \alpha D(z)\Delta T = \alpha D(z)(T - T_0)$$
$$= \begin{cases} \alpha D(z)\left(T_t - T_0 - \dfrac{T_t - T_c}{L_a} z\right) & L_a \le z \le 0 \\ \alpha D(z)\left(T_t - T_0 + \dfrac{T_h - T_t}{L_b} z\right) & 0 < z \le L_b \end{cases}$$

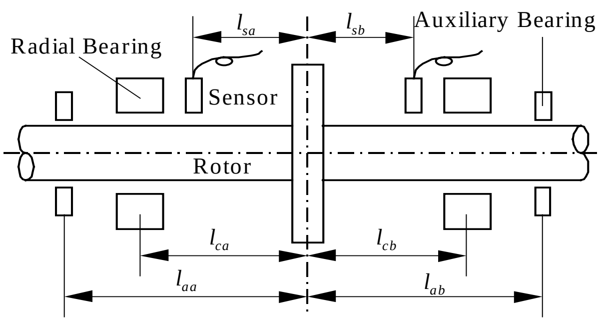

Fig. 4: Radial Bearing Structure

Because of the temperature gradient, the expansion at the position of the left and right radial bearings is different. So the axis will be inclined by temperature distribution. According to the geometric relationship in Fig. 4, the displacements at the position of the magnets and auxiliary bearings are respectively given by

$$\begin{cases} y_{ca} = \dfrac{-l_{ca} + l_{sb}}{l_s}\dfrac{\Delta D_{sa}}{2} - \dfrac{l_{ca} - l_{sa}}{l_s}\dfrac{\Delta D_{sb}}{2} \\ y_{cb} = \dfrac{l_{cb} - l_{sa}}{l_s}\dfrac{\Delta D_{sb}}{2} - \dfrac{l_{cb} - l_{sb}}{l_s}\dfrac{\Delta D_{sa}}{2} \end{cases}$$

$$\begin{cases} y_{aa} = \dfrac{-l_{aa} + l_{sb}}{l_s}\dfrac{\Delta D_{sa}}{2} - \dfrac{l_{aa} - l_{sa}}{l_s}\dfrac{\Delta D_{sb}}{2} \\ y_{ab} = \dfrac{l_{ab} - l_{sa}}{l_s}\dfrac{\Delta D_{sb}}{2} - \dfrac{l_{ab} - l_{sb}}{l_s}\dfrac{\Delta D_{sa}}{2} \end{cases}$$

At the same time, imbalance currents in the radial bearings are caused by both radial expansion and rotor displacement. The balance equations are satisfied by

$$\begin{cases} K_A \dfrac{(I_{A0} - \Delta i_{Da})^2}{(C_0 - \Delta D_{ca})^2} = K_B \dfrac{(I_{B0} + \Delta i_{Da})^2}{C_0^{\ 2}} \\ K_A \dfrac{(I_{A0} - \Delta i_{Db})^2}{(C_0 - \Delta D_{Db})^2} = K_B \dfrac{(I_{B0} + \Delta i_{Dbr})^2}{C_0^{\ 2}} \end{cases}$$

$$\begin{cases} K_A \dfrac{(I_{A0} - \Delta i_{ya})^2}{(C_0 - y_{ca})^2} = K_B \dfrac{(I_{B0} + \Delta i_{ya})^2}{(C_0 + y_{cal})^2} \\ K_A \dfrac{(I_{A0} - \Delta i_{yb})^2}{(C_0 - y_{cb})^2} = K_B \dfrac{(I_{B0} + \Delta i_{ybr})^2}{(C_0 + y_{cb})^2} \end{cases}$$

The total amount of current change is given by

$$\begin{cases} \Delta i_a = \Delta i_{Da} + \Delta i_{ya} \\ \Delta i_b = \Delta i_{Db} + \Delta i_{yb} \end{cases}$$

The contact equation is

$$|C_f| = \max\{|\Delta D_{aa} + y_{aa}|, |\Delta D_{ab} + y_{ab}|\}$$

Calculation results of expansion, displacement of the rotor, imbalance current under different temperatures, and the contact temperature for radial bearings are shown in Table 3.

SENSOR TEMPERATURE DRIFT

When sensor temperature drift is considered, the rotor expansion effect is ignored to simplify discussion.

Sensor Temperature Drift Character

Because of different sensor types and working ranges, the temperature characteristic are different, generally. The temperature characteristic is usually nonlinear. A small range near the working point of the sensors is considered as linear to simplify discussion.

Two kinds of sensor temperature character curve are shown in Fig. 5 and Fig. 6.

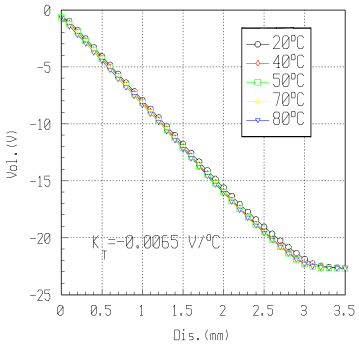

Fig. 5: Sensor Character with Single Power Supply

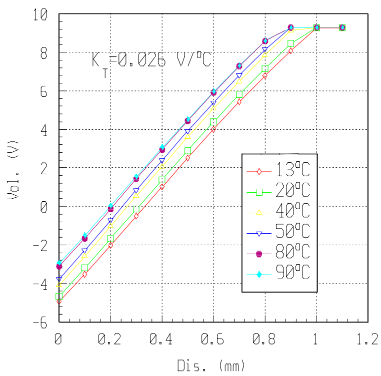

Fig. 6: Sensor Character with two Power Supplies

Table 3: Expansion, Displacement, Imbalance Current and Contact Temperature

	T_t=60℃	T_t=80℃	T_t=100℃	T_t=120℃
ΔD_{sa}	5.35e-6m	-5.35e-6m	-16.05e-6m	-26.75e-6m
ΔD_{sb}	-21.04e-6m	-31.56e-6m	-42.07e-6m	-52.59e-6m
ΔD_{ca}	27.46e-6m	19.21e-6m	10.97e-6m	2.73e-6m
ΔD_{cb}	-15.89e-6m	-23.84e-6m	-31.78e-6m	-39.73e-6m
ΔD_{aa}	47.11e-6m	41.05e-6m	34.99e-6m	28.93e-6m
ΔD_{ab}	-11.32e-6m	-16.98e-6m	-22.64e-6m	-28.30e-6m
y_{ca}	6.92e-6m	1.54e-6m	-3.84e-6m	-9.22e-6m
y_{cb}	-14.76e-6m	-19.99e-6m	-25.22e-6m	-30.45e-6m
y_{aa}	10.69e-6m	5.28e-6m	-0.124e-6m	-5.53e-6m
y_{ab}	-18.53e-6m	-23.73e-6m	-28.94e-6m	-34.14e-6m
Δi_a	-0.3952A	-0.2141A	-0.030A	0.1573A
Δi_b	0.4607A	0.6533A	0.8497A	1.0501A
T_{tc}	190℃ (Right Auxiliary bearing)			

Sensor Temperature Drift Effects on the System
Sensor temperature drift is related by its temperature coefficient, gain and temperature at working condition. The displacement of the rotor caused by the drift is

$$\Delta S = \frac{K_T}{K_S}\Delta T = \begin{cases} \frac{K_T}{K_S}\left(T_t - T_0 - \frac{T_t - T_c}{L_a}z\right) & L_a \le z \le 0 \\ \frac{K_T}{K_S}\left(T_t - T_0 + \frac{T_h - T_t}{L_b}z\right) & 0 < z \le L_b \end{cases}$$

The imbalance currents of the magnet caused by the displacement of the rotor are satisfied as follows

$$K_A\frac{(I_{A0} - \Delta i)^2}{(C_0 - \Delta S)^2} = K_B\frac{(I_{B0} + \Delta i)^2}{(C_0 + \Delta S)^2}$$

When contact between the rotor and the auxiliary bearings occurs, the balance equation is

$$C_f = \Delta S$$

Thrust Bearing
When drift in the axial direction occurs, the rotor will moved toward or away from the sensor of the bearing for layout A and C. Calculation results for two kinds of sensors are shown in Table 4 and Table 5.

Table 4: Displacement, Imbalance Current and Contact Temperature (K_T=0.0065)

	T_t=60℃	T_t=80℃	T_t=100℃	T_t=120℃
ΔS	-33.04e-6m	-49.56e-6m	-66.07e-6m	-82.59e-6m
Δi	-0.6607A	-0.9911A	-1.3215A	-1.6518A
T_{tc}	141℃ (Left Auxiliary Bearing)			

Table 5: Displacement, Imbalance Current and Contact Temperature (K_T=0.025)

	T_t=60℃	T_t=80℃	T_t=100℃	T_t=120℃
ΔS	65.0e-6m	97.5e-6m	130e-6m	162.5e-6m
Δi	1.30A	1.95A	2.60A	3.25A
T_{tc}	82℃ (Right Auxiliary Bearing)			

According to the calculation results, the sensor temperature drift has great effect on system characteristic for layout A and C. For layout B, the sensor temperature drift effect can be ignored.

Radial Bearing
The situation is the same for the expansion of the radial bearings. The axis will be inclined by temperature distribution. The displacements at the positions of the magnets and auxiliary bearings are respectively given by

$$\begin{cases} y_{ca} = \frac{-l_{ca} + l_{sb}}{l_s}\Delta S_{sa} - \frac{-l_{ca} + l_{sa}}{l_s}\Delta S_{sb} \\ y_{cb} = \frac{l_{cb} - l_{sa}}{l_s}\Delta S_{sb} - \frac{l_{cb} - l_{sb}}{l_s}\Delta S_{sa} \end{cases}$$

$$\begin{cases} y_{aa} = \dfrac{-l_{aa}+l_{sb}}{l_s}\Delta S_{sa} - \dfrac{-l_{aa}+l_{sa}}{l_s}\Delta S_{sb} \\ y_{ab} = \dfrac{l_{ab}-l_{sa}}{l_s}\Delta S_{sb} - \dfrac{l_{ab}-l_{sb}}{l_s}\Delta S_{sa} \end{cases}$$

Calculation results of rotor displacement, imbalance currents and contact temperature for radial bearings are shown in Table 6.

Table 6: Displacement, Imbalance Current and Contact Temperature (K_T=0.0065)

	T_t =60℃	T_t =80℃	T_t =100℃	T_t =120℃
ΔS_{sa}	6.08e-6m	-6.086e-6m	-18.26e-6m	-30.43e-6m
ΔS_{sb}	-23.93e-6m	-35.89e-6m	-47.86e-6m	-59.83e-6m
y_{ca}	15.73e-6m	-3.49e-6m	-8.74e-6m	-20.98e-6m
y_{cb}	-33.58e-6m	-45.48e-6m	-57.38e-6m	-69.28e-6m
y_{aa}	24.31e-6m	12.02e-6m	-0.28e-6m	-12.58e-6m
y_{ab}	-42.16e-6m	-53.99e-6m	-65.84e-6m	-77.68e-6m
Δi_a	0.3147A	0.0699A	-0.1748A	-0.4196A
Δi_b	-0.6716A	-0.9096A	-1.1476A	-1.3856A
T_{tc}	158℃ (Right Auxiliary Bearing)			

CONCLUSIONS

The thrust bearing is the main heating source of an AMB system in expander applications. System static precision is mainly affected by rotor expansion and sensor temperature drift. Both dimension and position precision is affected by rotor expansion. Affect of rotor dimension precision is decided by the characteristic of rotor material. Only by suitable structure design, selection of rotor material and appropriate arrangement can the dimensioning precision be controlled.

The position precision affected by rotor expansion is due to non-co-location of sensor and bearings. In an actual system, it is difficult to balance co-location and sensor temperature drift for thrust bearings.

System precision is not directly affected by auxiliary bearing location, but poor location can limit rotor expansion. Contact will easily happen if the arrangement of auxiliary bearings is not appropriately designed. So the layout C is the best choice for this situation.

The position precision is directly affected by sensor temperature drift, which is related to the sensor's temperature coefficient, gain and location. If you desire to reduce the affect on system precision by sensor temperature drift, all things being equal, select the sensor with the smaller coefficient and higher gain. Then layout B is the best selection.

Because of the large temperature gradient along the rotor in expander applications, temperature distribution must be considered. The precision of the thrust bearing is influenced by rotor expansion in the axial direction much more than in the radial direction. Therefore, the expansion in the radial direction can be ignored. Only position precision is affected by sensor temperature drift. The influence of sensor drift on radial bearings and thrust bearings is of the same magnitude along both radial and axial direction.

Effective reduction of the heating of the thrust bearing and its effects on AMB rotor precision can be obtained with accurate design of the thrust bearing, and appropriate selection and location of the sensors. The static precision of AMB systems can be improved by controlling heating sources and the way by which temperature affects the system.

REFERENCES

1. Zhang Gang, Coupled Electromechanical Dynamics of a Rotor-Active Magnetic Bearing System, PhD thesis, Xi'an Jiaotong University, April 1999.
2. Chen Liqun, Study on Precision Control and Application of Active Magnetic Bearings, PhD thesis, Xi'an Jiaotong University, April 1999.
3. Jiang Dachuan, Liu Shuqin, Yu Lei and Wang Shihu, Study for Designing the Construction Parameters of Electromagnetic Thrust Supporting Systems, Journal of Xi'an Jiaotong University, 1997(12).
4. R.J.Field, V.lannello, A Reliable Magnetic Bearing System for Turbomachinery, Proc. Sixth Int. Symposium on Magnetic Bearings, '98, Technomic Publishing, PA.

Nomenclature

C_{at} = gape of auxiliary bearings
C_0 = gape of bearings
D = rotor diameter
I_{A0} , I_{B0} = bias current of magnet
K_A , K_B = electromagnet geometric parameter
K_T = coefficient of sensor drift
K_S = sensor gain
L = rotor length
ΔS =displacement by sensor drift
t = temperature variables
T_c = temperature of cold side
T_h = temperature of hot side
T_t = temperature of thrust bearing
T_0 = initialize temperature
T_{tc} = temperature of collision
z = coordinate of axial direction
α = coefficient of expansion