Research on Redundancy of Weak Coupling Radial Magnetic Bearing

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***Abstract*—The weak coupling radial magnetic bearing structure and force balance compensation has been proposed in this paper. The force balance compensation of weak coupling radial magnetic bearing is simulated and comparison with bias current linearization. The research shows the force balance compensation can provide bigger electromagnetic force, the process of solving compensation matrix is simple, and the compensation current is more uniform. Meanwhile, The experimental results verify the feasibility of weak coupling radial magnetic bearing with redundant structure and force balance compensation.**

I. INTRODUCTION

Since the 1990s, aimed at how to further improve the reliability of magnetic bearing, many scholars, at home or abroad have done some studies in terms of actuators, controllers and sensors. In 1995, for radial magnetic bearing, bias current linearization method and algorithm of current distribution matrix was proposed by Eric H. Maslen[1]. Aimed at this method and algorithm, many scholars have conducted the confirmatory studies.

Based on bias current linearization theory, Myounggyu D. Noh describe the design and implementation of a fault tolerant magnetic bearing system for a turbo-molecular vacuum pump, the system is fault-tolerant design for actuators and position sensors of radial magnetic bearings[2]. Aimed at radial magnetic bearing in flexible magnetic suspension rotor , Uhn Joo Na in Texas A&M University use bias current linearization to solve the current distribution matrix of this structure, and use matlab software to simulate, the results show the linearized control forces can be realized up to certain combination of 5 poles failed for the 8 pole magnetic bearing. But with the number of failure coils increased, the stiffness and load capacity of magnetic bearings will decrease[3][4]. Ming-Hsiu Li studied on redundant control of magnetic bearings with flux coupling , and generalize the bias current linearization theory to the magnetic bearing with composite structure[5][6]. Satish Chand designed a three-pole magnetic bearings fault-tolerant controller based on nonlinear fuzzy logic control, when any of the three coils is failure, the rotor can stably suspended, and can obtain a good suspension properties[7].

For radial magnetic bearings with the configuration of multi-pole, independently driven coils, Wu Buzhou use the method of generalized bias current linearization to linearize the electromagnetic force. Then a redundant scheme of controller reconfiguration is developed on the basis of this method[8]. According to a six-core radial active magnetic bearing, the fault tolerant control method of displacement sensor based on coordinate transformation is studied by Cui Donghui, and the feasibility of this method has been verified through experiment[9][10].

II. REDUNDANCY SCHEME FOR WEAK COUPLING RADIAL MAGNETIC BEARINGS

Figure 1 shows the radial magnetic bearing structure based on Eric H. Maslen's idea. It works on the magnetic coupling between the poles, therefore can be called redundant structure for strong coupling radial magnetic bearing.

Figure 2 shows redundancy scheme for the radial magnetic bearing proposed in this paper. In the scheme, pole as an independent unit and pole pairs completely separated from each pole of the structure. The arrangement of using NNSS can further weaken the magnetic coupling between the magnetic poles, so it is called weak coupling radial magnetic bearing redundant structure. As shown in the two structures, each pole has a group of independent coils. The remaining coil can be reconstituted a new magnetic bearing systems when failure of anyone coil.

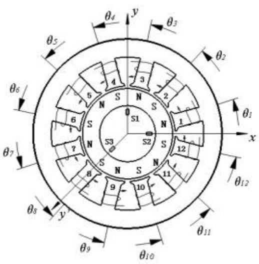


Figure 1.The strong coupling radial magnetic bearing structure

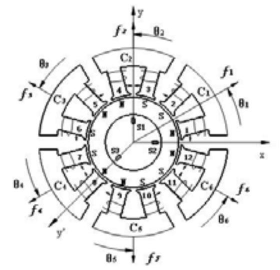


Figure 2. The weak coupling radial magnetic bearing structure

III. WORKING PRINCIPLE OF BIAS CURRENT LINEARIZATION AND FORCE BALANCE COMPENSATION

Eric H. Maslen and other scholars present the bias current linearization theory for strongly coupled radial magnetic bearing structure shown in Figure 1.

The theory is carried out by some reallocation of current control strategy[1], when part of the pole failure, which flux essentially redistribution and compensation.

A. Force balance compensation of weak coupling radial magnetic bearing

The magnetic poles coupling of the weak coupling magnetic radial magnetic bearings can be ignored, so the each poles pair can be used as an independent unit for analysis.

Define F_j as magnetic force of the jth electromagnetic pole, A as magnetic pole area, θ_j as orientation angle of the jth magnetic pole, δ_j as average value of air gap between the jth magnetic pole and rotor, δ_0 as air gap when rotor is the Equilibrium position, μ_0 as vacuum permeability, i_{2j-1} *and* i_{2j-1} as coil current of two poles for the j_{th} magnetic pole respectively, counter clock wise is order, N as the number of coil turns of the windings on a single pole.

Since each pole pair can be considered to be independent, thus it has the same impact for magnetic force by increasing the current of anyone pole coil in the same pole pair. It is assumed that the current in the two magnetic poles coil of the same pole pair is equal. that is $i_{j(1)}=i_{j(2)}$, make $i_{j(1)}=i_{j(2)}=i_j$, and record $i_{sj}=i_{j(1)}+i_{j(2)}$.

According to the electromagnetic force equation, the electromagnetic force of single magnetic pole pair is expressed as follow :

$$F_j = \mu_0 A N^2 \cdot \frac{(i_{j(1)}+i_{j(2)})^2}{4\delta_j^2} \cdot \cos\alpha = \mu_0 A N^2 \cdot \frac{i_{sj}^{\ 2}}{4\delta_j^2} \cdot \cos\alpha \qquad (1)$$

Where α represents half angle of adjacent poles, $\alpha=\pi/2n$, n represents total number of pole pairs of radial magnetic bearing,

$$\delta_j = \delta_0 - x\cos\theta_j - y\sin\theta_j \qquad (2)$$

When the rotor is at the equilibrium position, $\delta_j=\delta_0$.

If

$$k = \frac{\mu_0 A N^2 \cos\alpha}{4\delta_0^2} \qquad (3)$$

Then

$$F_j = k i_{sj}^{\ 2} \qquad (4)$$

The magnetic force on the rotor can be obtained as follows:

$$\begin{cases} F_x = \mathbf{F}\mathbf{D}_x \\ F_y = \mathbf{F}\mathbf{D}_y \\ \mathbf{F} = \begin{bmatrix} F_1 & F_2 & F_3 & F_4 & F_5 & F_6 \end{bmatrix} \\ \mathbf{D}_x = \begin{bmatrix} \cos\theta_1 & \cos\theta_2 & \cos\theta_3 & \cos\theta_4 & \cos\theta_5 & \cos\theta_6 \end{bmatrix}^T \\ \mathbf{D}_y = \begin{bmatrix} \sin\theta_1 & \sin\theta_2 & \sin\theta_3 & \sin\theta_4 & \sin\theta_5 & \sin\theta_6 \end{bmatrix}^T \end{cases} \qquad (5)$$

B. Rule for force balance compensation

According to failure modes of the weak coupling coil radial magnetic bearing, failure can be divided into two categories.

The first category failure: partial failure of a pole pair coil, that is, one coil is invalid.

The second category failure: a pole coil to fail completely, that is, two coils are invalid.

The electromagnetic force of magnetic pole pair can be achieved by increasing the current of the other coil when the first category failure to occur, that is, called the first class compensation.

The magnetic bearing will regain the same magnetic force as before coil failure or until the magnetic saturation by increasing the current of adjacent or near magnetic pole pair when the second category failure to occur, that is, called the second class compensation. The rule is the minimum energy and the minimum sum of compensation current for the method.

Define the current matrix without any coil failure as **I**.

Define a current compensation matrix as

$$\mathbf{M}_r = \begin{bmatrix} \cdots & 1 & 1 & 1 & 1 & 1 & 1 & \cdots \end{bmatrix}_{1\times12}^T$$

Define the initial current of each magnetic pole coil as

$$\mathbf{I}_r = \begin{array}{c} \\ p_{(1)} \\ p_{(2)} \\ j_{(1)} \\ j_{(2)} \\ q_{(1)} \\ q_{(2)} \\ \\ \end{array} \begin{bmatrix} \cdots & & & & & & & \\ & i_p & & & & & & \\ & & i_p & & & & & \\ & & & i_j & & & & \\ & & & & i_j & & & \\ & & & & & i_q & & \\ & & & & & & i_q & \\ & & & & & & & \cdots \end{bmatrix}_{12\times12}$$

Where $p=j-1$, $q=j+1$。

The current compensation matrix assigns compensated current to each coil,

$$\mathbf{I} = \mathbf{I}_r \mathbf{M}_r$$

(1)The first class compensation

The compensation would be achieved by increasing the current of the $j_{(2)}$ coil when the $j_{(1)}$ coil of the j_{th} magnetic pole pair invalid.

$$\begin{array}{cccccccccc} \mathbf{M}_r = & [& \cdots & 1 & 1 & 0 & 2 & 1 & 1 & \cdots\ ]_{1\times12}^T \\ & & & p_{(1)} & p_{(2)} & j_{(1)} & j_{(2)} & q_{(1)} & q_{(2)} & \end{array}$$

The compensation method is based on the maximum current in the coil $i_{max} \geqslant 2i_j$. It is necessary to adjust the current of adjacent magnetic pole pair coil when the maximum current in the coil $i_{max}<2i_j$.

（2）The second class compensation

Assumed the j_{th} magnetic pole pair failure completely, the compensation criteria are as follows: the force compensation for $j+1$ and $j-1$ should be provided by the nearest magnetic pole. The compensation matrix $\mathbf{M}_r$ follows as:

$$\begin{array}{cccccccccc} \mathbf{M}_r = & [& \cdots & \sqrt{\frac{F_p+F_j}{F_p}} & \sqrt{\frac{F_p+F_j}{F_p}} & 0 & 0 & \sqrt{\frac{F_q+F_j}{F_q}} & \sqrt{\frac{F_q+F_j}{F_q}} & \cdots\ ]_{1\times12}^T \\ & & & p_{(1)} & p_{(2)} & j_{(1)} & j_{(2)} & q_{(1)} & q_{(2)} & \end{array}$$

IV. SIMULATION OF BIAS CURRENT LINEARIZATION AND FORCE BALANCE COMPENSATION

Both magnetic flux density and magnetic force has been simulated using ANSYS on strong coupling and weak coupling radial magnetic bearing under bias current linearization and force balance compensation. The basic parameters of structure design are shown in Table I.

TABLE I. DESIGN PARAMETERS OF RADIAL MAGNETIC BEARING

	Parameter	Value
x_0	Single-side air gap	0.3 mm
I_m	Maximum current	6 A
N	coil turn of a single pole	56
A_a	Cross-section area of a magnetic pole	500 mm^2

A. Simulation of bias current linearization on strong coupling structure

Using bias current linearization, when there is no coil failure, the current distribution matrix of strong coupling radial magnetic bearing with 12 poles in figure 1 is obtained as $\mathbf{W}_q$ and when coil 1 and coil 2 are in failure, the corresponding current distribution matrix is obtained as $\mathbf{W}_{q(1,2)}$.

$$W_q=\begin{bmatrix} 0.0631 & 0.2745 & 0.2328 \\ -0.1520 & -0.1532 & 0.1228 \\ -0.0257 & -0.1662 & 0.2235 \\ 0.1245 & -0.1998 & -0.1172 \\ 0.0484 & 0.0015 & 0.4503 \\ -0.1280 & 0.6745 & 0.2237 \\ -0.1859 & 0.3555 & 0.3560 \\ -0.1980 & 0.2277 & 0.3595 \\ -0.2206 & 0.1385 & 0.2710 \\ -0.1112 & -0.2600 & 0.2903 \\ 0.0947 & -0.2570 & -0.1892 \\ -0.1737 & 0.5632 & 0.1310 \end{bmatrix} \quad W_{q(1,2)}=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.1856 & 0.0743 & 0.2120 \\ -0.1318 & 0.2256 & 0.0690 \\ -0.1247 & -0.0519 & 0.1460 \\ 0.0412 & -0.0202 & 0.0180 \\ -0.0288 & 0.1127 & -0.0580 \\ -0.2575 & 0.1808 & 0.0203 \\ -0.1753 & 0.2168 & 0.1707 \\ -0.1279 & -0.0323 & 0.1464 \\ -0.0267 & 0.1115 & -0.0428 \\ 0.1423 & 0.2453 & -0.0030 \end{bmatrix}$$

According to the equation $\mathbf{I}=\mathbf{W}\mathbf{I}_c$, the current in each coil can be obtained. Then in the equilibrium state, there are relationships as $F_x=0$, $F_y=49$N.

According to the current distribution matrixes above, the magnetic flux density and magnetic force in the air gap of each magnetic pole can be obtained and then shown in figure 3 and 4. The magnetic forces in X and Y direction are shown in Table II.

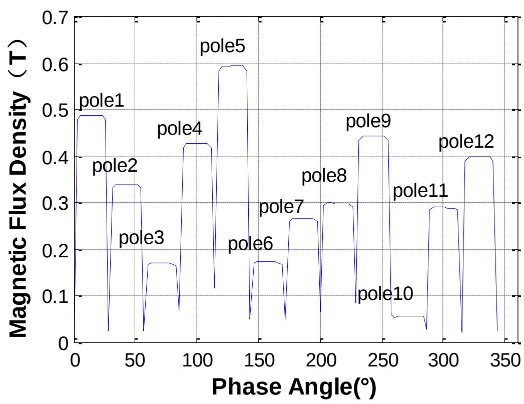


Figure 3. Magnetic flux density in the air gap before failure.

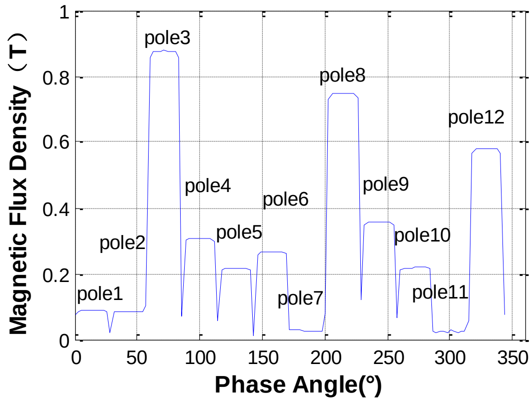
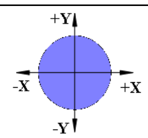


Figure 4. Magnetic flux density in the air gap after failure

TABLE II. MAGNETIC FORCE IN X、Y DIRECTION



Working condition / *Magnetic force direction*		Magnetic force before failure(N)	Magnetic force when coil 1and coil 2 are in failure (N)
	+X	105	109
	-X	101	110
	+Y	121	177
	-Y	74	129

B. Simulation of bias current linearization on weak coupling structure

Using bias current linearization, when there is no coil failure, the current distribution matrix of weak coupling radial magnetic bearing with 12 poles in figure 2 is obtained as $\mathbf{W}_r$ and when coil 1 and coil 2 are in failure, the corresponding current distribution matrix is obtained as $\mathbf{W}_{r(1,2)}$.

$$\mathbf{W}_r=\begin{bmatrix} 0.0810 & 0.1676 & 0.0109 \\ 0.0810 & 0.1676 & 0.0109 \\ -0.1170 & 0.1107 & -0.1145 \\ -0.1170 & 0.1107 & -0.1145 \\ 0.0662 & -0.1573 & 0.2611 \\ 0.0662 & -0.1573 & 0.2611 \\ 0.0872 & -0.1973 & 0.0343 \\ 0.0872 & -0.1973 & 0.0343 \\ 0.1125 & 0.0372 & -0.1099 \\ 0.1125 & 0.0372 & -0.1099 \\ 0.0737 & -0.1887 & 0.2631 \\ 0.0737 & -0.1887 & 0.2631 \end{bmatrix} \quad \mathbf{W}_{r(1,2)}=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.0967 & -0.0713 & -0.1221 \\ -0.0967 & -0.0713 & -0.1221 \\ 0.1080 & -0.1258 & 0.0010 \\ 0.1080 & -0.1258 & 0.0010 \\ 0.0022 & -0.0204 & -0.0115 \\ 0.0022 & -0.0204 & -0.0115 \\ 0.0972 & -0.0692 & -0.1217 \\ 0.0972 & -0.0692 & -0.1217 \\ 0.1078 & 0.1270 & 0.0008 \\ 0.1078 & 0.1270 & 0.0008 \end{bmatrix}$$

With the same principle, the magnetic flux density and magnetic force in the air gap of each magnetic pole can be obtained and then shown in figure 5 and 6. The magnetic forces in X and Y direction are shown in Table III.

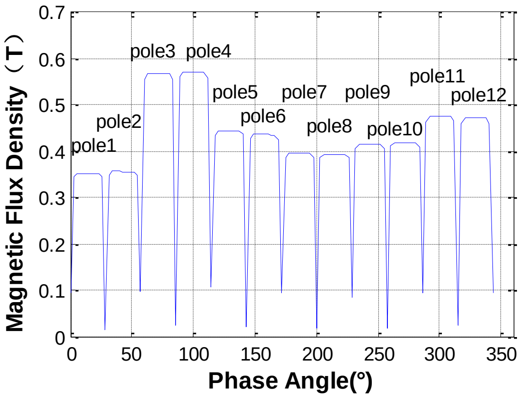


Figure 5. Magnetic flux density in the air gap before failure

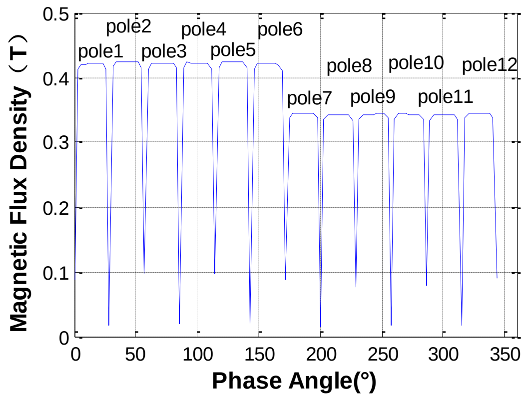


Figure 7 Magnetic flux density in the air gap before failure

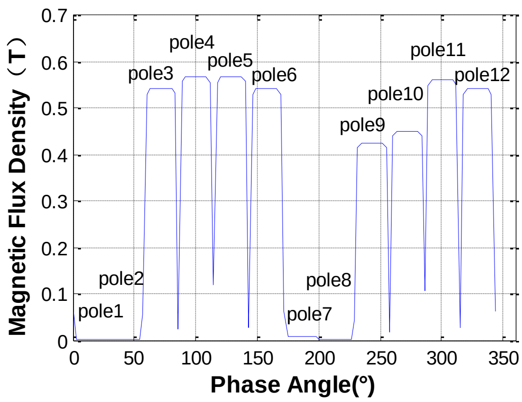


Figure 6. Magnetic flux density in the air gap after failure

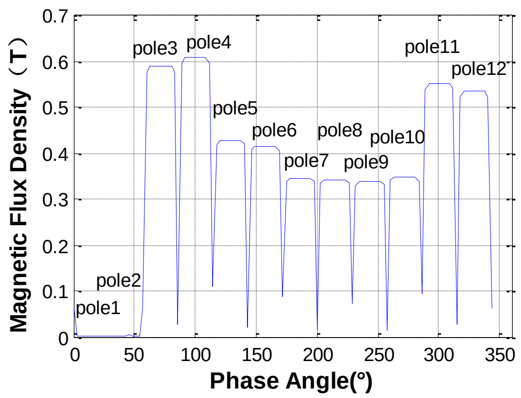


Figure 8 Magnetic flux density in the air gap after failure

TABLE III. MAGNETIC FORCE IN X、Y DIRECTION

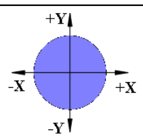
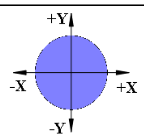
Working condition / ***Magnetic force direction***		Magnetic force before failure(N)	Magnetic force when coil 1and coil 2 are in failure (N)
	+X	99	94
	-X	99	94
	+Y	148	167
	-Y	99	119

TABLE IV. MAGNETIC FORCE IN X、Y DIRECTION

Working condition / ***Magnetic force direction***		Magnetic force before failure(N)	Magnetic force when coil 1and coil 2 are in failure (N)
	+X	104	104
	-X	104	104
	+Y	144	180
	-Y	95	131

C. Simulation of force balance compensation on weak coupling structure

Using force balance compensation, when there is no coil failure, the current matrix of weak coupling radial magnetic bearing with 12 poles in figure 2 can be directly obtained as $\mathbf{I}$ and when coil 1 and coil 2 are in failure, the corresponding current distribution matrix is also obtained as $\mathbf{I}_{(1,2)}$.

$$\mathbf{I} = [1.8462\ 1.8462\ 1.8462\ \ 1.8462\ \ 1.8462\ \ 1.8462\ \ 1.5\ \ 1.5\ 1.5\ 1.5\ \ 1.5\ \ 1.5]$$

$$\mathbf{I}_{(1,2)} = [0\ \ 0\ \ 2.6251\ \ 2.6251\ \ 1.8462\ \ 1.8462\ \ 1.5\ \ 1.5\ 1.5\ 1.5\ \ \ 2.3788\ \ \ 2.3788]$$

With the same principle, the magnetic flux density and magnetic force in the air gap of each magnetic pole can be obtained and then shown in figure 7 and 8. The magnetic forces in X and Y direction are shown in Table IV.

V. ANALYSIS AND COMPARISON BETWEEN TWO CONTROL METHODS

The basic principle of bias current linearization is using a bias current i_0 and two control currents i_x, i_y to express the magnetic force in X, Y direction as equation(4). With this principle, a current distribution matrix can then be deduced as $\mathbf{W}$ which illustrates the relationship between i_x, i_y and i_1~i_{12} to realize the current distribution.

The basic principle of force balance compensation is to analyse each pair of magnetic poles as an independent unit, ignoring the magnetic coupling between them. According to force balance compensation, the current in each coil can then be obtained and the current compensation is thus realized.

Based on the comparison of magnetic flux density and magnetic force in two structures when there is no coil failure and when coil 1 and coil 2 are in failure, conclusions can be made as followed.

- For bias current linearization, there are multiple solutions which means the outcome of compensation is not unique. Conversely, for force balance compensation, the solution is unique.
- For bias current linearization, the distribution of magnetic field is not uniform when there is no coil failure and when coil 1and coil 2 are in failure, so the magnetic force produced is relatively small. For force balance compensation, owing to the principle of minimum energy, the sum value of compensation current is then the least and the distribution of current and magnetic flux is relatively uniform, so under the unsaturation limit in magnetic material, magnetic force produced is larger.
- For bias current linearization, the calculation process is complicated. Different initial values will lead to a great deviation in the outcome when solving the current distribution matrix, so repeated calculation is needed for it. For force balance compensation, the calculation process of the matrix is simple. As long as the failure condition is known, corresponding compensation matrix can be obtained quickly according to the compensation principle, thus greatly simplifying the calculation process.

VI. FORCE BALANCE COMPENSATION EXPERIMENT OF WEAK COUPLING RADIAL MAGNETIC BEARING

To verify the feasibility of force balance compensation in weak coupling radial magnetic bearing, the bearing structure with 6 pole pairs is simplified to the basic form with one pole pair and the rotor is simplified as a armature which is shown in figure 9. The whole experimental device is shown in figure 10 and the design parameters are listed in Table V.

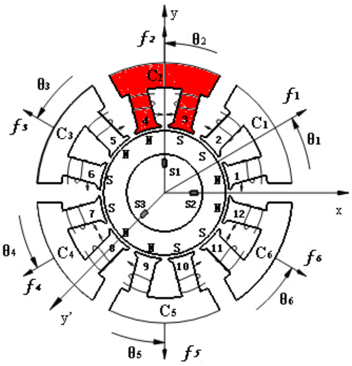


Figure 9 Experimental principle of force balance compensation

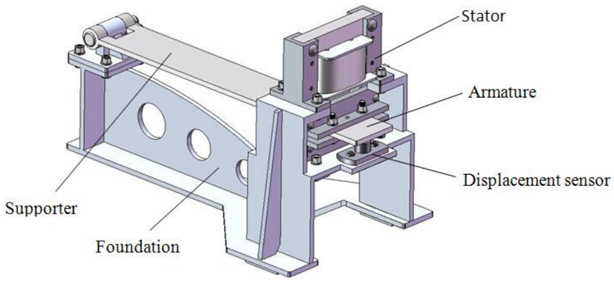


Figure 10 Experimental device of force balance compensation

TABLE V. DESIGN PARAMETERS OF MAGNETIC SUSPENDED REDUNDANT EXPERIMENTAL DEVICE

	Parameter	Value
A	Cross-section area of the armature	480 mm^2
x	Total air gap	1 mm
N	Turn of coil 1	400
N	Turn of coil 2	100
i_m	Maximum current	3A

A. *Control principle of experimental system*

Considering the generality, there are two independent coils with different turns winded onto the armature. Independent control can be realized on these two coils and the control principle is shown in figure11.

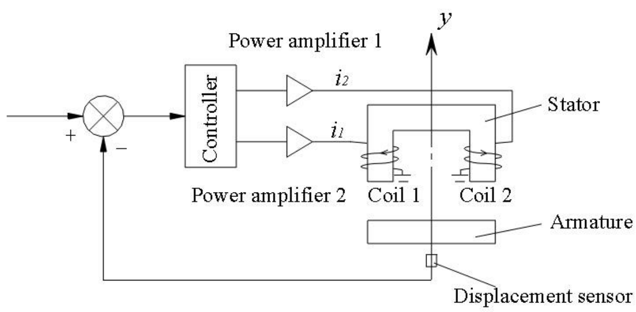


Figure 11 Control principle of experimental device

B. *Experimental result analysis*

Experimental research on the reconfiguration process is carried out on the experimental device of weak coupling radial magnetic bearing corresponding to coil 1 failure and coil 2 failure respectively. Firstly, the armature is suspended steadily and then a fault order is given to make a zero output of the failed coil, compensating the other coil at the same time. PID parameters are adjusted before the experiment to make sure the steady suspension of the armature.

Dynamic property curves of reconfiguration process under coil 1 failure and coil 2 failure are shown in figure 12 and 13 respectively.

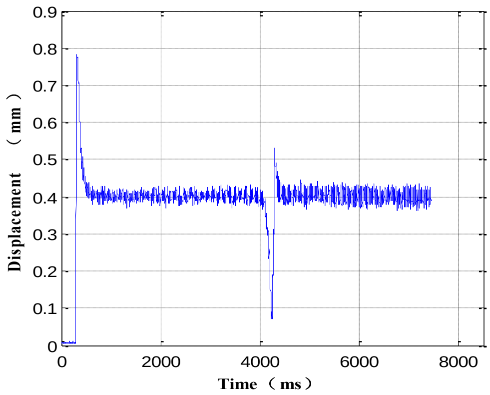


Figure 12 Reconfiguration process curve under coil 1 failure

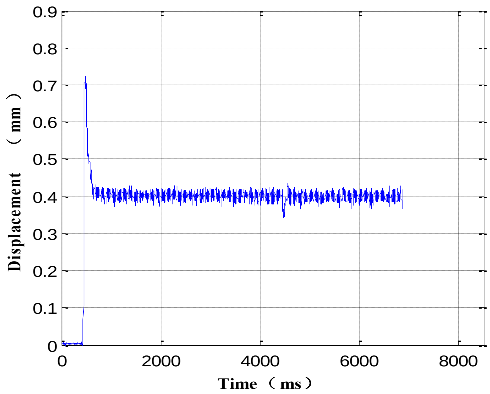


Figure 13 Reconfiguration process curve under coil 2 failure

From the two figures above, for coil 1 failure, the reconfiguration process needs a long time and the vibration of armature is quite large. For coil 2 failure, the reconfiguration process only needs a short time and the vibration of armature is really small. So coil 2 failure has a small influence on the steady-state performance of the system.

The experiment verifies the feasibility of force balance compensation in weak coupling radial magnetic bearing.

VII. CONCLUSIONS

The redundant structure of weak coupling radial magnetic bearing can realize the redundant reconfiguration. Compared to the strong coupling structure, the weak coupling structure has a couple of advantages. Bias current linearization is suitable for both strong and weak coupling structure. Compared to bias current linearization, force balance compensation has a couple of advantages.

VIII. ACKNOWLEDGEMENTS

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REFERENCES

[1] Eric H. Maslen and David C. Meeker, “Fault Tolerance of Magnetic Bearings by Generalized Bias Current Linearization,” *IEEE Transactions on Magnetics*, vol. 313, no. 3, pp. 2304-2314, 1995.

[2] Myounggyu D.Noh, Seong-Rak Cho,et al, “Design and Implementation of a Fault-Tolerant Magnetic Bearing System for Turbo-Molecular Vacuum Pump,” *IEEE/ASME Transactions on Mechatronics*, vol. 10, no. 6, pp. 626-631, 2005.

[3] Uhn Joo Na, “Fault-tolerant control of heteropolar magnetic bearings,” *College Station: Texas A&M University*, 1999.

[4] Uhn Joo Na, Alan Palazzolo, “Optimized Realization of Fault-Tolerant Heteropolar Magnetic Bearings,” *Journal of Vibration and Acoustics*, vol. 122, pp. 209-221, 2000.

[5] Ming-Hsiu Li, “Fault tolerant control of homopolar magnetic bearings and circular sensor arrays,” *College Station: Texas A&M University*, 1999.

[6] Ming-Hsiu Li, Alan B.Palazzolo, Andrew Kenny, et al. Kascak, “Fault-Tolerant Homopolar Magnetic Bearings,” *IEEE Transactions on Magnetics*, vol. 40, no. 5, pp. 3308 -3318, 2004.

[7] Praveen Kumar Agarwal, Satish Chand, “Fault-tolerant control of three-pole active magnetic bearing,” *Expert Systems with Applications*, vol. 36, pp. 12592-12604, 2009.

[8] Wu Buzhou, Sun Yanhua, Wang Shihu,et al, “Coil Fault-tolerant Control for Radial Active Magnetic Bearings,” *Chinese Journal of Mechanical Engineering*, vol. 41, no. 6, pp. 157-162, 2005.

[9] Cui Donghui, “Research on key technology of magnetic bearing with high reliability,” *Nanjing University of Aeronautics and Astronautics*, 2010.

[10] Cui Donghui, XuLongxiang, “Fault tolerant control of radial active magnetic bearing based on coordinate transformation,” *Control and Decision*, vol. 25, no.9, pp. 1420-1430, 2010.