Analysis and Experimental Study on Uncertain Fault of Active Magnetic Bearing Displacement Sensor

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Abstract **─** Active magnetic bearing (AMB) has been gradually applied to high speed rotating equipment to suspend rotor as it has many advantages, but some uncertain faults always appeal in the process of application. Meanwhile, displacement sensor is a key equipment of AMB control system, but when it is used in high speed atomizer, some uncertain problems are happened, such as expected range cannot be adjusted, and data characteristics cannot match well in the X-Y direction. In view of these problems, we gather electrical parameters in different frequencies, and establish the corresponding equivalent circuit models, to analyze the reasons of uncertain faults. Then we propose the high frequency electrical parameters characteristic analysis method to realize reliable judgment and reveal the essence of uncertain faults. Finally, comparative experiments are carried to verify the analysis methods, the results show that the electrical parameters of fault characteristic analysis method established for uncertain faults of displacement sensor has good theoretical and practical value.

Index Terms **─** AMB, data characteristic, displacement sensor, uncertain fault.

I. INTRODUCTION

As the greatest potential and high-efficiency bearing, AMB has lots of advantages, such as contactless, no need of lubrication, no wear, low noise, and can reach very high rotation speed [1], so it has important application values in the field of rotary machinery and equipment. The closed loop control system is essential to stably suspend the rotor because AMB is an open loop unstable system. Therefore, the reliability of control system is a basic guarantee for the system operation. High precision displacement sensor is one of the key components of system, but it is always influenced by uncertain factors that exist in some abnormal states in the process of design, manufacture, commissioning and operation. Such as expected range cannot be adjusted, and data characteristics cannot match well in the X-Y direction, which would bring huge risk to AMB. So these uncertain faults must be effectively solved in the actual application.

Meanwhile, the study on fault diagnosis of AMB displacement sensor is very important as it is applied to the industrial area, and some great research results are obtained [2-4]. Article [3] proposed an on-line diagnosis scheme for sensor faults in an active magnetic bearing system equipped with built-in force transducers. Article [4] introduced wavelet transform to fault diagnosis of redundant displacement sensor for AMB. However, these diagnosis methods are only suitable to the deterministic faults, but cannot be used to solve uncertain faults.

Therefore, aiming to solve uncertain faults of atomizer AMB displacement sensor, different frequency equivalent circuit models are built, and data characteristics of high frequency electrical parameter are analyzed, which would be used to diagnose some uncertain faults of displacement sensor. Apparently, this research work is innovative and pioneering to the study and diagnose of the uncertain fault of the AMB displacement sensor.

II. AMB APPLIED IN ATOMIZER

There are many factories that require tail gas treatment, for example, the desulphurization and denitrification of tail gas in thermal power plants, the absorbent is usually atomized in order to achieve better purification. The principle of atomizer described in this article is to atomize the absorbent by virtue of the centrifugal force, which is generated via the high speed motor, as shown in Fig. 1.

As centrifugal force is the basis of the atomizer, so the design speed of the atomizer is usually very high, basically reaching more than 10000r/min. However, the traditional rolling bearing is easily damaged at high speed and cannot meet the application requirements. Therefore, AMB is the best technical choice for rotor levitation in such high speed device. From the perspective of the

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atomizer structure as shown in Fig. 1, the rotor is vertical layout, therefore, the axial AMB should produce force to balance the gravity of the rotor and atomization wheel, and the corresponding AMB structure is shown in Fig. 2.

Fig. 1. High speed atomizer.

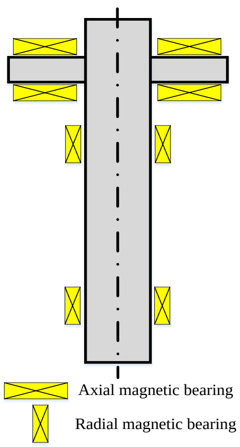

Fig. 2. The AMB structure of atomizer.

III. UNCERTAIN FAULTS DESCRIPTION OF AMB IN ATOMIZER

Displacement sensor commissioning is the basic work for AMB control system. According to the atomizer control demand, five degrees of freedom need to install the displacement sensors [1]. Actually, in order to reduce the nonlinear error, we usually adopt the differential transformer type displacement sensor, and the structure is shown in Fig. 3.

In the process of commissioning, we found a series of uncertain faults, such as the expected range cannot be adjusted in the Y direction in the bottom of AMB displacement sensor, and X-Y direction data characteristic cannot match well within the same sensor, here we refer to the radial magnetic bearing.

In fact, uncertain fault refers to a kind of unpredictable fault which has the characteristics of randomness, fuzziness and greyness, and the evolution mechanism is not clear and occurrence process is gradual. The diagnosis of uncertain faults often needs field expert experience, but recent years, random mathematics [5], fuzzy theory [6], and mathematical methods (such as grey theory [7] and evidence theory), have been introduced to the study of uncertain problems to predict failures.

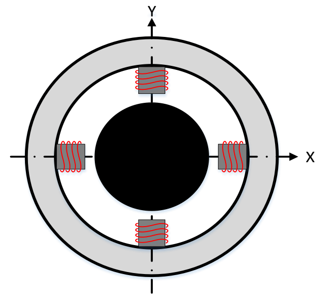

Fig. 3. The structure of differential transformer type displacement sensor used in AMB.

In this paper, uncertain faults happened in AMB displacement sensor of the atomizer are described as:

1) Even if the circuit amplification factor is adjusted in the whole range, Y direction cannot achieve the target range.

2) In the same frequency, the electrical parameters of the inductor coil cannot match well between X and Y direction.

Unlike conventional deterministic faults, uncertain faults have the characteristics of progressive and latent. Thus, traditional fault analysis methods have been unable to solve the uncertain problems. Otherwise, if uncertain faults are not properly confirmed and solved scientifically, it would bring great safety risk to the operation of the AMB system.

IV. ANALYSIS ON THE UNCERTAIN FAULT MECHNISM OF DISPLACEMENT SENSOR

A. Equivalent circuit model of winding

In order to solve the above problems of AMB displacement sensor, it is necessary to analyze the equivalent circuit model and electrical parameter characteristics. A single pole inductor is shown in Fig. 4. In addition to inductance L, it is usually accompanied by loss resistance R_L and distributed capacitance C_L. C_L usually has little impact on circuit in DC or low frequency state, but it cannot be ignored in high frequency state. So according to the working frequency of the circuit, a single pole inductor has three equivalent circuit models, which are described as below.

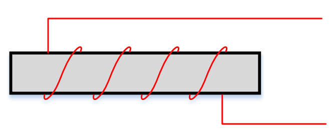

Fig. 4. A single pole inductor.

B. DC steady state equivalent circuit model of single pole inductor winding

When an inductor winding is connected to the DC circuit that reaches a steady state, the winding can be regarded as an ideal resistance R_L. The corresponding equivalent circuit model is shown in Fig. 5, and the equivalent impedance is expressed as (1):

$$Z_e = R_L. \quad (1)$$

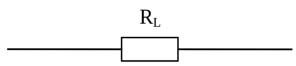

Fig. 5. DC steady state equivalent circuit model.

C. Low frequency equivalent circuit model of single pole inductor winding

When an inductance winding is connected into low frequency AC circuits, the winding can be regarded as an ideal resistance R_L in series with an inductance L. The corresponding equivalent circuit model is shown in Fig. 6, and the equivalent impedance is expressed as (2):

$$Z_e = R_L + j\omega L. \quad (2)$$

Fig. 6. Low frequency equivalent circuit model.

D. High frequency equivalent circuit model of single pole inductor winding

When an inductance winding is connected into high frequency AC circuits, in addition to an ideal resistance R_L in series with an inductance L, there exists a distributed capacitance C_L. Especially when the winding has turn-to-turn short circuit, the distributed capacitance effect would be much more serious. The corresponding equivalent circuit model is shown in Fig. 7 and the equivalent impedance is expressed as (3):

$$Z_e = \frac{(R_L + j\omega L)\frac{1}{j\omega C_L}}{R_L + j\omega L + \frac{1}{j\omega C_L}}$$

$$= \frac{R_L}{(1-\omega^2 LC_L)^2 + (\omega C_L R_L)^2} + j\omega \frac{L(1-\omega^2 LC_L) - R_L{}^2 C_L}{(1-\omega^2 LC_L)^2 + (\omega C_L R_L)^2}. \quad (3)$$

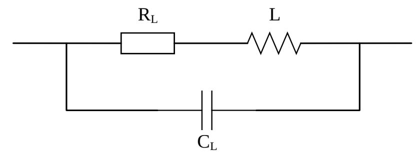

Fig. 7. High frequency equivalent circuit model.

In (1) (2) (3), $\boldsymbol{\omega = 2\pi f}$. Where, $\boldsymbol{f}$ is the working frequency of circuit. Here (1) (2) (3) can be written as the standard formula of reactance, as shown in (4):

$$Z_e = R_e + jX_e. \quad (4)$$

Therefore, Quality Factor (Q) of the circuit is calculated as (5):

$$Q = \frac{X_e}{R_e}. \quad (5)$$

Q is an important parameter to measure inductance components, which is the ratio of reactance ($\boldsymbol{X_e}$) to equivalent loss resistance ($\boldsymbol{R_e}$) refer to the AC at a particular frequency. Certainly, Q is influenced by the winding DC resistance, skeleton, dielectric loss, and the core material. But in the same AMB displacement sensor, all poles have the same inductor winding, so the data characteristic of all electrical parameters are basically consistent.

E. Analysis of winding electrical parameter

According to field expert experience, electrical parameters of the displacement sensor installed in the atomizer are measured via handheld LCR meter and analyzed in 0.1 kHz, 1 kHz, 10 kHz and 100 kHz. Here we mainly analyzed inductance L, quality factor Q, DC resistance DCR and equivalent reactance $\boldsymbol{Z_e = R_e + jX_e}$ in four directions, the results are shown in Table 1, Fig. 8, Fig. 9, Fig. 10 and Fig. 11.

Table 1: Electrical parameters of displacement sensor used in atomizer

Frequency	**0.1 kHz**					**1 kHz**				
Parameters	$R_e(\Omega)$	L(mH)	$X_e(\Omega)$	Q	DCR(Ω)	$R_e(\Omega)$	L(mH)	$X_e(\Omega)$	Q	DCR(Ω)
X+	2.106	0.811	0.510	0.242	2.103	2.169	0.809	5.083	2.343	2.102
X-	2.094	0.790	0.496	0.237	2.086	2.148	0.788	4.951	2.305	2.083
Y+	2.064	0.782	0.491	0.238	2.061	2.126	0.781	4.907	2.308	2.060
Y-	2.108	0.738	0.464	0.220	2.106	***2.598***	***0.727***	***4.568***	***1.758***	2.105
Frequency	**10 kHz**					**100 kHz**				
Parameters	$R_e(\Omega)$	L(mH)	$X_e(\Omega)$	Q	DCR(Ω)	$R_e(\Omega)$	L(mH)	$X_e(\Omega)$	Q	DCR(Ω)
X+	6.080	0.783	49.197	8.092	2.101	112.727	0.603	378.876	3.361	2.100
X-	5.892	0.763	47.941	8.136	2.082	109.152	0.591	371.336	3.402	2.081
Y+	5.833	0.757	47.564	8.154	2.058	109.608	0.583	366.309	3.342	2.060
Y-	***20.981***	***0.377***	***23.688***	***1.129***	2.103	***98.786***	***0.197***	***123.779***	***1.253***	2.102

Note: the abnormal data is marked with bold italic and underscore, such as ***2.598***.

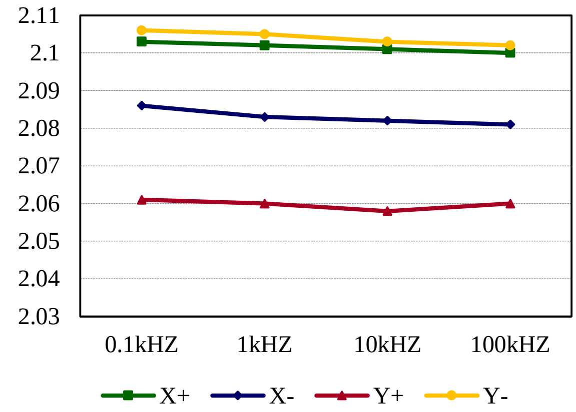

Fig. 8. DCR (Ω) comparison diagram.

It can be seen from Fig. 8 that the DC steady state resistances DCR of the four poles are basically the same, which indicates that the windings have no open circuit fault.

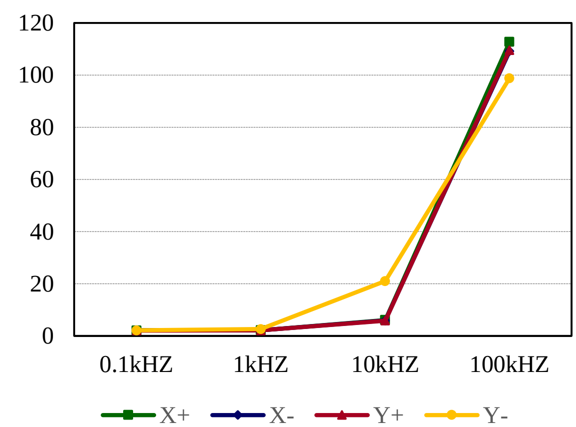

Fig. 9. R_e (Ω) comparison diagram.

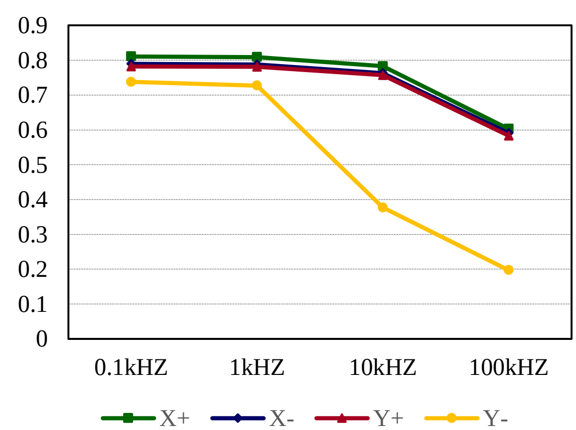

Fig. 10. L (mH) comparison diagram.

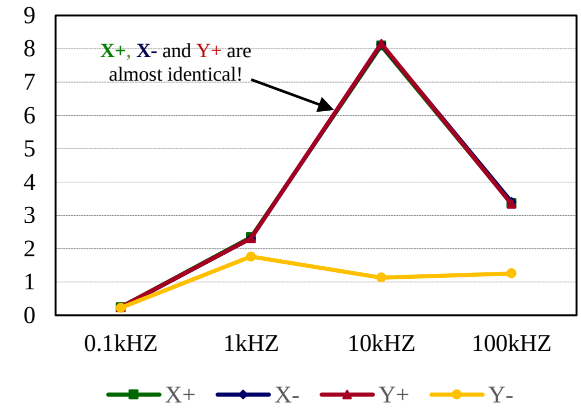

Fig. 11. Q comparison diagram.

Figure 9 and Fig. 10 indicate that in the low frequency, equivalent resistance R_e and inductance L of the four poles are not very different with each other. But as the frequency increases, the gaps between Y-direction and the other three directions is increasing rapidly, which means it exists abnormal condition. When the inductance L and the distributed capacitance C_L of the circuit meet certain conditions, the circuit will resonate. And the resonant frequency f_0 can be obtained by setting the imaginary part of equation (3) to zero, as shown in (6) and (7):

$$L(1-{\omega_0}^2 LC_L)-{R_L}^2 C_L=0, \qquad (6)$$

$$f_0=\frac{\omega_0}{2\pi}\,. \qquad (7)$$

When the working frequency of the circuit f is greater than f_0, the inductance L will be significantly less, so the corresponding Q also decreases sharply, as shown in Fig. 11. According to Fig. 7 and equation (3), we can found that the higher the frequency of the circuit (f), the smaller the equivalent inductive reactance ($\boldsymbol{X_e}$), which is because the greater the distributed capacitance (C_L).

Combined with the circuit theory [8] and the above analysis, as the frequency increases, the Y-direction in the equivalent resistance (Re), equivalent inductance (L) and quality factor (Q) do not match with the other three poles. And the main reason is that the Y-inductor has a larger capacitance (C_L), which eventually leads to the range cannot be adjusted to expected goal. Although the actual inductor winding will not work in high frequency, analysis on characteristics of high frequency electrical parameters can provide a very useful way to solve this kind of uncertain faults.

V. EXPERIMENTAL STUDY ON UNCERTAIN FAULT OF DISPLACEMENT SENSOR

A. Experimental design and data analysis

In order to further verify the conclusion of uncertain faults analysis on AMB displacement sensor. Firstly, we rebuilt two fully functional displacement sensors for comparative analysis, then we intentionally damaged the insulation layer of X+ direction winding of one displacement sensor and marked it as A, another one was marked B that maintained functional integrity.

In accordance with Table 1, we used the same methods to test and analyze the same electrical parameters of A and B, the results are shown in Table 2 and Table 3.

Table 2: Electrical parameters of displacement sensor A

Frequency	**0.1 kHz**					**1 kHz**				
Parameters	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)
X+	2.391	0.799	0.502	0.210	2.388	***4.248***	***0.697***	***4.397***	***1.031***	2.388
X-	2.269	0.791	0.497	0.219	2.265	2.342	0.789	4.957	2.117	2.264
Y+	2.294	0.814	0.511	0.223	2.287	2.367	0.811	5.096	2.153	2.289
Y-	2.392	0.788	0.495	0.207	2.394	2.468	0.786	4.939	2.001	2.393
Frequency	**10 kHz**					**100 kHz**				
Parameters	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)
X+	***24.074***	***0.382***	***24.002***	***0.997***	2.388	***83.114***	***0.159***	***99.903***	***1.202***	2.388
X-	6.554	0.758	47.627	7.267	2.264	117.191	0.592	371.964	3.174	2.264
Y+	6.809	0.777	48.820	7.170	2.287	119.286	0.606	380.761	3.192	2.286
Y-	6.725	0.754	47.375	7.045	2.392	116.795	0.590	370.708	3.174	2.392

Note: the abnormal data is marked with bold italic and underscore, such as ***4.248***.

Table 3: Electrical parameters of displacement sensor B

Frequency	**0.1 kHz**					**1 kHz**				
Parameters	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)
X+	2.355	0.802	0.504	0.214	2.350	2.429	0.800	5.027	2.069	2.349
X-	2.237	0.794	0.499	0.223	2.232	2.310	0.792	4.976	2.154	2.232
Y+	2.279	0.816	0.513	0.225	2.268	2.348	0.814	5.115	2.178	2.268
Y-	2.367	0.791	0.497	0.210	2.355	2.434	0.789	4.957	2.037	2.355
Frequency	**10 kHz**					**100 kHz**				
Parameters	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)	R_e(Ω)	L(mH)	X_e(Ω)	Q	DCR(Ω)
X+	6.764	0.766	48.129	7.115	2.350	119.784	0.603	378.876	3.163	2.347
X-	6.562	0.760	47.752	7.277	2.232	118.520	0.594	373.221	3.149	2.232
Y+	6.818	0.779	48.946	7.179	2.266	120.556	0.609	382.646	3.174	2.265
Y-	6.723	0.756	47.500	7.065	2.355	118.347	0.592	371.965	3.143	2.353

Table 2 indicates that the electrical parameters of A cannot keep the consistency. The reason is that C_L of X+ direction impacts on the circuit is much greater than other poles, and much more serious in high frequency. The experimental results is consistent with characteristic of atomizer.

Table 3 indicates that the electrical parameters of B can keep the consistency as B is a fully functional displacement sensor.

Therefore, insulation layer damaged in inductor winding would lead the C_L is much greater, which results in the electrical parameters be inconsistent, and other uncertain problems.

B. Commissioning and operation analysis

After individual testing and analyzing of A and B, we installed A and B to the atomizer respectively, and found that only B can meet the requirements of the atomizer, and operational state as shown in Fig. 12.

Conversely, A failed to achieve the intended range adjustment problems. The results indicate that the two uncertain faults described in part III have intrinsic relevance, and the essential reason is that excessive distributed capacitance exists between inductance windings.

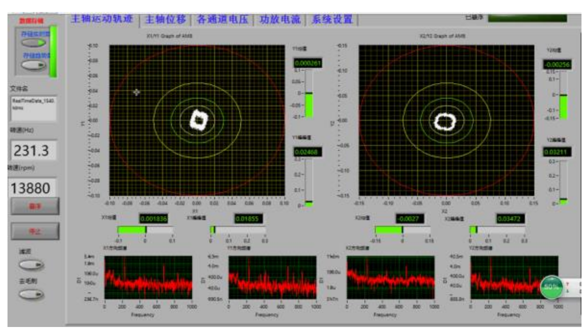

Fig. 12. Operational state of the atomizer.

VI. CONCLUSION

Uncertain faults are common problems of the AMB displacement sensor. Due to latent and progressive characteristics, uncertain faults are often difficult to be found in normal condition, and it may lay hidden danger to the safe and stable operation of the AMB. Based on AMB used in atomizer, combining with the expert experience and electrical parameters characteristic analysis technology, this article reveals the fundamental reasons of two uncertain faults of displacement sensor, and solves the problem of uncertain fault in actual application. In addition, the analyze method based on the characteristics of high frequency electrical parameter for inductive displacement sensor proposed in this article provides a new solution and diagnosis method to solve this kind of uncertain faults in AMB. Furthermore, the experimental results show that the method has certain theoretical and practical value.

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