Calculation and Experiment of Electromagnetic Force of the Axial AMB used in HTR-PM Main Helium Blower Prototype and its Dual Material Selection Method

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Abstract ─ The Active Magnetic Bearing (AMB) is used in the main helium blower in the High Temperature Reactor-Pebble-bed Modules (HTR-PM) which is being constructed in Shandong province, China. The axial AMB is very large and works under extreme conditions. The calculation deviation of the electromagnetic force of the axial AMB was studied experimentally. Through measuring *B-H* curve of the material in large range of magnetic field intensity, considering flux leakage in calculation, and considering residual magnetism and the change of the gas gap in measurement, the calculation deviation reduces to 10%, with most values less than 5%. The material selection method of the axial AMB working under extreme conditions was studied experimentally. Through measuring the electromagnetic force when the stator and the thrust disc are made of different materials, it's found that the force mostly depends on the stator. Combined with the analysis of the stress distribution of the stator and the thrust disc under working condition, the dual material selection method is proposed. That is, the stator material should have good magnetic properties and its mechanical properties are not very important, however, the thrust disc material should have good mechanical properties, and its magnetic properties are not very important.

Index Terms ─ Active magnetic bearing, axial bearing, calculation deviation, electromagnetic force, extreme conditions, material selection.

I. INTRODUCTION

The Active Magnetic Bearing (AMB) suspends the rotor by electromagnetic force. Compared with traditional mechanical bearing, the AMB has advantages such as no-contact, long-life and controllability [1]. In the High Temperature Reactor- Pebble-bed Modules (HTR-PM) which is being constructed in Shandong province, China, the AMB is used in the main helium blower [2,3]. A prototype of the main helium blower is manufactured for research, and its AMB is designed by Tsinghua University [4,5]. The AMB of the blower prototype is large. The diameter of the axial bearing is about 600 mm. The axial load is about 10 tons, and the bearing will work in extreme conditions, which is near magnetic saturation. So the calculation of the electromagnetic force during design should be quite accurate.

Many researchers calculated the electromagnetic force using the Maxwell Stress Tensor Method (MSTM) and the Finite Element Method (FEM), and reduced the calculation errors from point of elements and nodes [6-8]. Nehl and Field [6] improved the force calculation accuracy for electromagnetic devices with small air gaps by adaptive mesh refinement using first order tetrahedral element using MSTM. Onuki et al. [7] proposed a smoothing method to calculate electromagnetic force more accurately using the Boundary Element Method (BEM) as a complement to the FEM and MSTM. Shi and Rajanathan [8] improved the force calculation accuracy of MSTM by selecting appropriate integration path and the potential interpolation points within the FEM. Except the MSTM, other methods are adopted by the researchers to calculate the electromagnetic force, such as the Reluctance Network Method (RNM) [9] and Lorentz Force Method (LFM) [10]. However, commercial software usually uses Virtual Work Method (VWM) and FEM to calculate the electromagnetic force, such as ANSYS Maxwell [11] and MagNet [12]. Compared with other methods, the VWM can deal with complex problems and is not sensitive to the integration path. As the algorithm improves, the calculation results by the commercial software are more and more accurate, and are usually regarded as reference values [13,14].

Unfortunately, the calculation results by ANSYS Maxwell have large deviation in the authors' early work of designing the axial AMB used in the main helium blower prototype. Theoretically, the deviation between

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the calculated force and the actual value comes from both calculation and measurement. The calculation error mainly composes of two parts. The first part is the magnetic properties of the materials used in calculation, which could be looked up in the handbooks, such as literature [15]. These properties may be different from the actual ones. The second part is the calculation model, which usually ignores flux leakage for simple. The measurement error depends on specific experiment and is rarely mentioned in other literatures [6-10]. It will be discussed below.

In this paper, firstly, the deviation between the calculated force and the experimental value of the axial AMB used in the main helium blower prototype is studied. Both the calculation error and the measurement error are considered. At first, the *B-H* curve of the materials are measured, especially under large magnetic field intensity. Then, the leakage flux is considered in the calculation model. At last, the actual value is measured carefully in the experiment. The deviation then is reduced by considering the above factors.

Secondly, material selection method for the axial AMB working under extreme conditions is studied. It's difficult to find a kind of material with both good mechanical properties and good magnetic properties [15]. Research about material selection for the axial AMB is rare, some papers that seem relevant don't concern this problem [16,17]. In this paper, different materials are used to make the bearing stator and the thrust disc, and the different influences of the stator and the thrust disc are researched by experiment. The stress distribution of the stator and the thrust disc is analyzed under working condition. At last, the materials selection method for the large axial bearing working in extreme condition is proposed.

II. EXPERIMENT AND CALCULATION

A. Measurement of *B-H* curve of the materials

The most important magnetic properties of a material for calculating the electromagnetic force is *B-H* curve, where B is the magnetic flux density, and H is the magnetic field intensity.

Materials of the axial AMB stator and thrust disc used in the blower prototype are the same, a kind of low alloy steel, denoted by M-steel. The *B-H* curve of this material could be looked up in handbook [15]. However, the low alloy steel has complex composition and heat treatment process, and both of them will change the *B-H* curve [15]. So the data from handbook is usually different from the actual one. At the same time, the data from handbook is only for low-intensity magnetic field, however the axial bearing of the blower prototype will work under high-intensity magnetic field. During calculation, the extension part of the curve will be deduced with some method, and then some error may be produced. To reduce the calculation error, the *B-H* curve of M-steel should be measured practically in large range of magnetic intensity.

In this paper, including M-steel, the *B-H* curves of used materials are measured with a soft magnetic tester, MATS-2010SD [18]. The sample is made into a ring and its size is shown in Fig. 1.

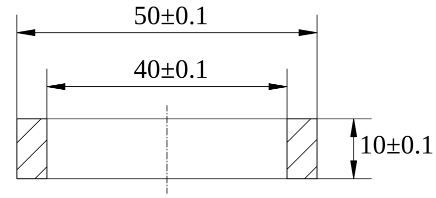

Fig. 1. Size of the magnetic material sample ([mm]).

B. Experiment for electromagnetic force

An equipment is established to measure the electromagnetic force, shown in Fig. 2. The equipment has the same size as the axial AMB of the blower prototype, with a thrust disc having a diameter of 600 mm. Actually, the equipment is also used to prove the design of the axial AMB. The thrust disc is fixed on a foundation with a magnetic isolation shim between them which is made of stainless steel. A bearing stator is also fixed on the foundation through three force testing sensors. When the coils in the stator have current, the force between the stator and the thrust disc could be measured by the sensors. It should be noted that the actual force is the sum of these three sensors' values. The current in stator is from 0 to 60 A, and the electromagnetic force is about from 0 to 10^5 N. The gas gap is from 0.7 mm to 1.5 mm.

In this paper, the measurement error of the electromagnetic force under certain current and certain gas gap comes from two aspects. The first one is residual force under zero current coming from gravity of the stator and the residual magnetism. The second one is the change of the gas gap under large electromagnetic force. In this paper the residual force is subtracted, and the gas gap is the actual value adjusted by the nuts under a certain current. Through these efforts, the measurement error is reduced.

In some experiments, the stator and the thrust disc are made of the same material, e.g., M-steel, which is used to prove the design of the AMB and to be compared with the calculation. In some other experiments, they are made of different materials to study the different influences of the stator and the thrust disc on the electromagnetic force. It will be discussed below.

C. Calculation for electromagnetic force

For simple, the magnetic flux density B in the gas gap shown in Fig. 2 could be calculated by equation (1), ignoring magnetic field in metal [1]:

$$B = \mu_0 NI/(2s), \tag{1}$$

where μ_0 is permeability of vacuum, N is number of windings in a single groove of the stator, I is current in the windings, and s is gas gap. And then the electromagnetic force would be calculated by equation (2):

$$F = B^2 A/(2\mu_0), \tag{2}$$

where F is the magnetic force, and A is the projected area of the flux. The above method has large error in equation (1) and it's only fit for initial design of the AMB.

In this paper, the electromagnetic force is calculated by the commercial software, ANSYS Maxwell [11]. A model as same as the actual experiment equipment is established, as shown in Fig. 3. The magnetic field in the metal, the actual *B-H* curve of the material, and the flux leakage are all considered in the model.

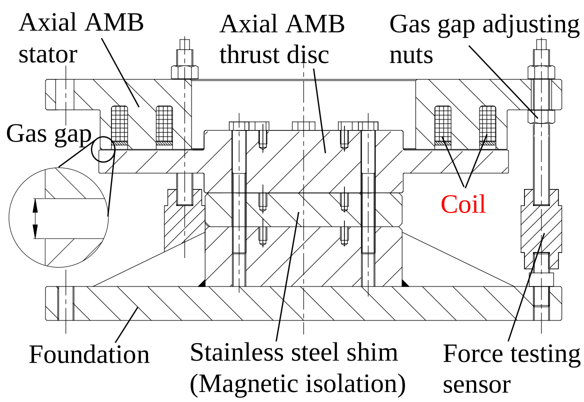

Fig. 2. The experiment equipment.

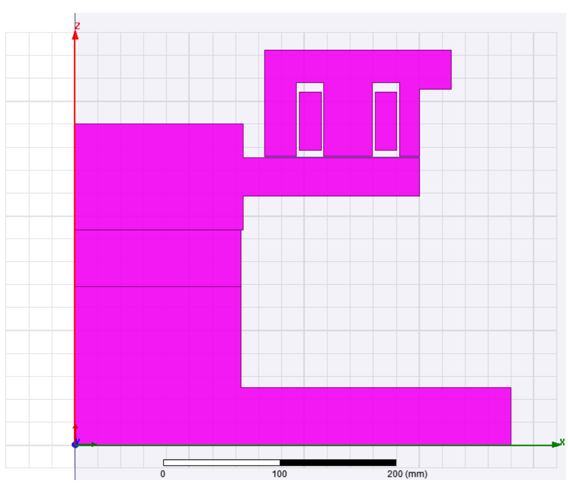

Fig. 3. Calculation model of the axial AMB for electromagnetic force.

D. Material selection method

In this section the stator and the thrust disc are made of different materials to study their different influences on the electromagnetic force. Two kinds of materials are used, as shown in Fig. 4. DT4C is a kind of soft magnetic iron with better magnetic properties and worse mechanical properties [19]. 20CrMo is a kind of low alloy steel with better mechanical properties [20] and worse magnetic properties, named 4120 in ASTM [21]. Their mechanical properties are shown in Table 1.

The stress distributions of the stator and the thrust disc under working conditions are analyzed. The stator is static, however, the thrust disc rotates under a speed of maximum 4,800 rpm [4,5] and has interference fit with the mandrel [22]. At the same time, there is an attractive force of most 10 tons between them. The stress is calculated by the commercial software, ANSYS Mechanical APDL [23], with the same material properties for both the stator and the thrust disc, such as Young's modulus of 210 GPa, Passion's ratio of 0.3, and density of 7850 kg/m^3.

According to the different influences on the force and the different stress distributions under working condition, the material selection method for the axial AMB is determined.

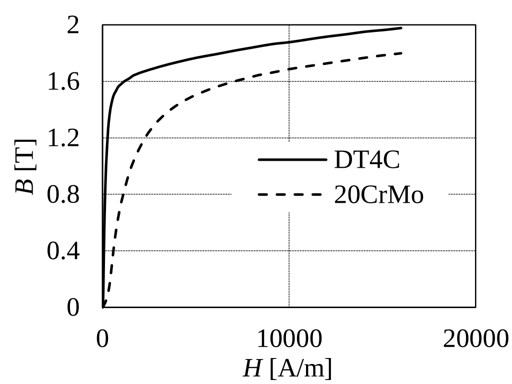

Fig. 4. *B-H* curves of DT4C and 20CrMo from measurement.

Table 1: Mechanical properties of DT4C and 20CrMo [19, 20]

Properties	DT4C	20CrMo
Tensile stress / MPa	≥265	≥885
Yield strength / MPa	≈100	≥685
Hardness (HV)	≤195	≥300
Young's modulus / GPa	≈210	≈210
Poisson's ratio	0.25~0.3	0.25~0.3

III. RESULTS AND DISCUSSION

A. Comparison of *B-H* curves of material between handbook and measurement

The *B-H* curve of the material M-steel is shown in Fig. 5. The values from handbook [15] and from measurement have large difference especially under high magnetic intensity, which would result in large deviation between calculation and experiment. There is similar phenomenon in Figs. 6~8, showing the *B*-*H* curve of C45 carbon steel, DT4C and 20CrMo respectively. C45 carbon steel is a kind of common carbon structural steel, which is used to make the foundation shown in Fig. 2. As a matter of fact, it's a general phenomenon that the values from handbook are accurate enough under low magnetic intensity, but not fit for accurate calculation under high magnetic intensity. The main reason of these difference is that both the composition and the heat treatment process of the material will change its magnetic properties.

Another problem of the values from handbook [15] is lack of data under magnetic field of more than 16000 A/m. ANSYS Maxwell [11] will extend the range of *B*-*H* curve with interpolation method, which will bring some certain error, as shown in Fig. 9. So measured *B*-*H* curve in the range of working conditions should be supplied for accurate calculation. In the blower prototype, the axial AMB worked under high-intensity filed, so the *B*-*H* curve of M-steel are measured up to 24000 A/m, as shown in Fig. 5. That ensured the accuracy of the calculation.

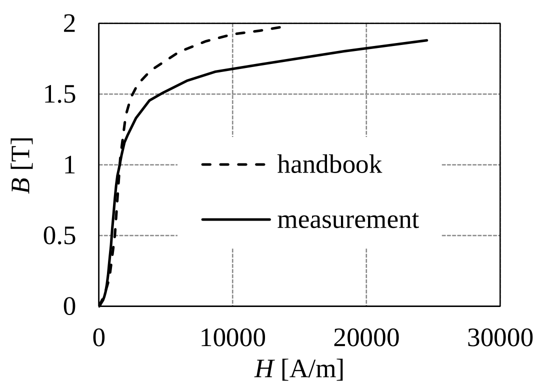

Fig. 5. *B*-*H* curve of M-steel, from handbook [15] and from measurement.

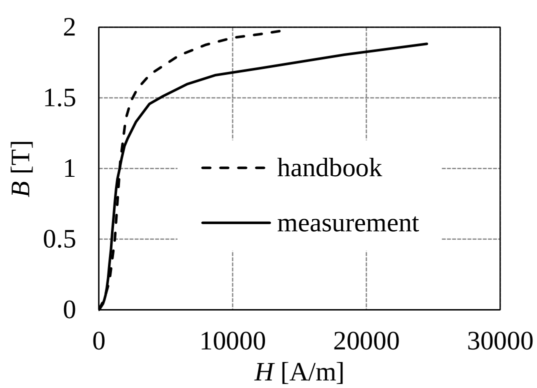

Fig. 6. *B*-*H* curve of C45 carbon steel, from handbook [15] and form measurement.

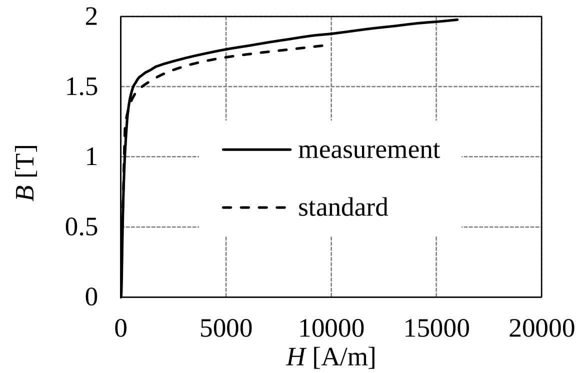

Fig. 7. *B*-*H* curve of DT4C, from standard [19] and from measurement.

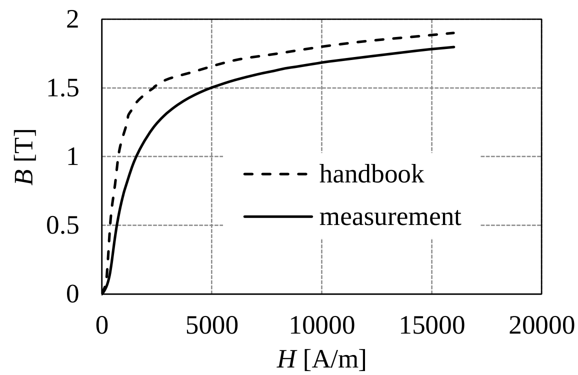

Fig. 8. *B*-*H* curve of 20CrMo, from handbook [15] and from measurement.

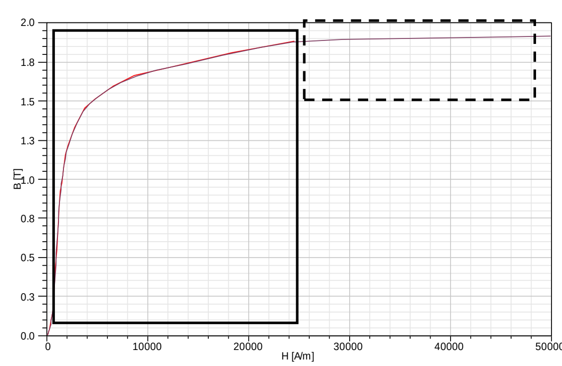

Fig. 9. Extended *B*-*H* curve of M-steel, produced by ANSYS Maxwell [11] with interpolation method, whose measured data is in solid line box and extended part is in dash line box.

B. Deviation of electromagnetic force between calculation and experiment

The typical distribution of the magnetic flux in the stator and the thrust disc is shown in Fig. 10, calculated with the model shown in Fig. 3. The experiment and calculation of the electromagnetic force of the axial AMB used in the blower prototype is shown in Fig. 11. The gas gaps are 0.8 mm and 1.1 mm, and the current is from 5 A to 60 A.

It's shown that, through efforts mentioned above, including measuring *B-H* curve of M-steel in large range of magnetic intensity, considering flux leakage in calculation, and considering residual force and the change of the gas gap in experiment, the deviation of the calculation values could be smaller than 10%. For most values, it's less than 5%. Because the magnetic tester's measurement accuracy for the *B-H* curve is about 1%~2% [18], the limitation of the calculation deviation is about 4% according to equation (2). That is to say, for most values, the deviation of the calculation is close to the limitation.

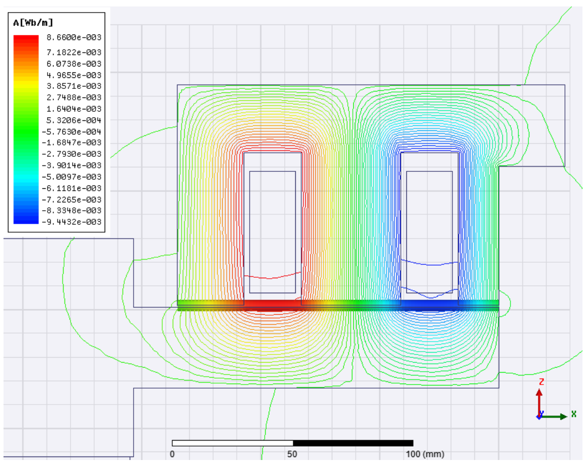

Fig. 10. Distribution of the magnetic flux in the axial AMB.

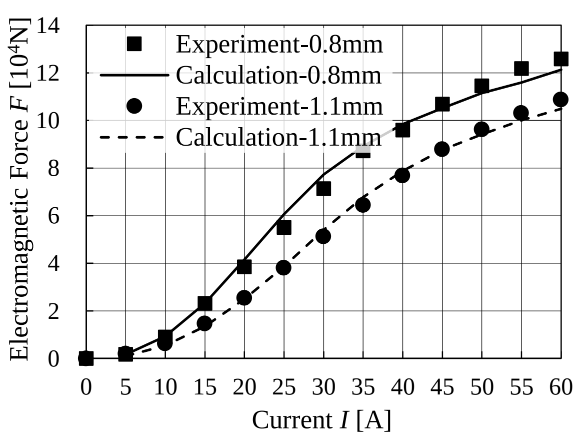

Fig. 11. Comparison between calculation and experiment of electromagnetic force, under two gas gaps, 0.8 mm and 1.1 mm.

C. Different influence on electromagnetic force and different stress distributions of bearing stator and thrust disc

In this section, two kinds of materials, DT4C and 20CrMo, are used to make the stator and the thrust disc. Their *B-H* curves from measurement are shown in Fig. 4. It can be seen that the permeability of DT4C is quite larger than the one of 20CrMo.

Measured electromagnetic force is shown in Fig. 12, with the stator and the thrust disc are made of DT4C or 20CrMo, and 0.8 mm gas gap. It can be seen that the force mostly depends on the material of the stator. That is to say, the stator material should have good magnetic properties to obtain large electromagnetic force. However, the magnetic properties of the thrust disc are not very important.

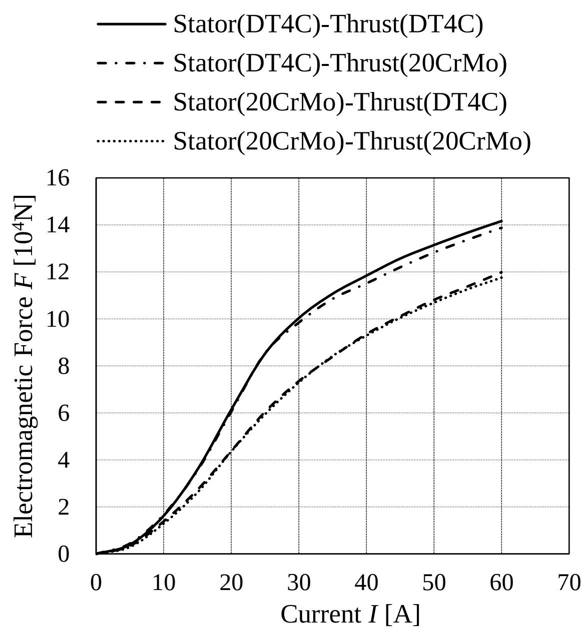

Fig. 12. Measured electromagnetic force, with the stator and the thrust disc made of DT4C or 20CrMo, under 0.8 mm gas gap.

The stress distributions of the stator and the thrust disc under working conditions are shown in Figs. 13 and 14 respectively. The working conditions include attractive electromagnetic force of 10 tons between the stator and the thrust disc, a rotation speed of 4,800 rpm for the thrust disc, and the interference fit of 0.25 mm in diameter between the thrust disc and the mandrel. Both the stator and the thrust disc have the same material properties, including Young's modulus of 210 GPa, Passion's ratio of 0.3, and density of 7850 kg/m^3.

It can be seen, the maximum Mises stress of the thrust disc is about 210 MPa; however the one of the stator is only 14.4 MPa. Considering a safety factor of 1.5~2.0, the yield strength of the thrust disc material should be larger than 350~400 MPa, and the one of the stator material should be larger than only 22~29 MPa.

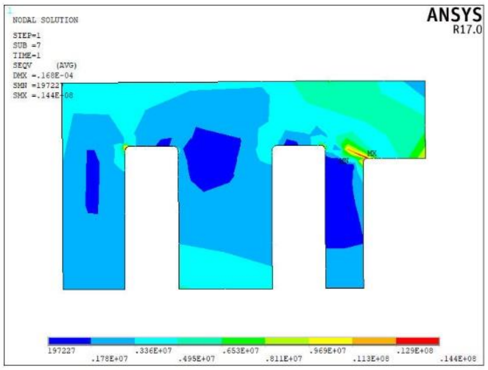

Fig. 13. Mises stress distributions of the stator under working condition.

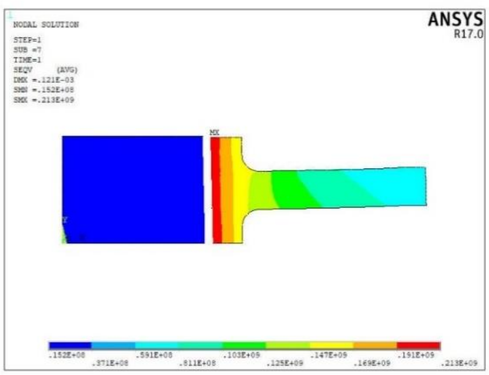

Fig. 14. Mises stress distributions of the thrust disc under working condition.

D. Dual material selection method

According to section III. C, the axial AMB stator has more important influence on the electromagnetic force, so its material should have good magnetic properties. And it doesn't need very good mechanical properties. However, the thrust disc should have good mechanical properties because of harder working condition, and doesn't need very good magnetic properties. The above description is called "dual material selection method" for the axial AMB.

Under extreme working condition like the blower prototype, it's difficult to find a kind of material with both good magnetic properties and good mechanical properties. In the blower prototype, the stator and the thrust disc used the same material, M-steel. As a matter of fact, M-steel is expensive and has complex heat treatment to improve the magnetic properties. So it's not the optimal solution. With the dual material selection method proposed in this paper, the stator and the thrust disc all have more options.

IV. CONCLUSION

Through some efforts, including measuring *B-H* curve of the material in large range of magnetic field intensity, considering flux leakage in calculation, and considering residual force and the change of the gas gap in measurement, the calculation deviation of the electromagnetic force of the axial AMB used in the main helium blower prototype is reduced to 10%. For most calculation values, the deviation is less than 5%, close to the limitation depending on measurement accuracy of the magnetic tester.

When the axial AMB stator and the thrust disc use different materials, the electromagnetic force is mostly depended on the material of the stator. The stator material should have good magnetic properties, and its mechanical properties are not very important. However, the thrust disc material should have good mechanical properties, and its magnetic properties are not very important. This "dual material selection method" make the materials of the stator and the thrust disc have more options.

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