Design of Axial Active Magnetic Bearing with High Load Capacity for Low Pressure Centrifugal Chiller

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ABSTRACT

Comparing with medium-pressure chiller, low-pressure chiller usually has better system efficiency. At the same capacity, however, the radius of impellers in low-pressure compressor must be increased due to using higher specific volume refrigerants. In general, it means this kind of chillers have heavier structure and results in larger chiller room occupancy. Larger radius of impeller not only increases manufacturing cost but also enforces the axial bearing force during rated operation condition. Especially for active magnetic bearing (AMB) application, the load capacity of axial bearing force is one of the critical issues that leads to cost reduction or not. In this research, we developed an axial AMB using permanent magnets to provide the basic axial force of the thrust disk. This design allows the impeller can support larger axial load but is dangerous for output force reversed. Therefore, our design is particularly suitable for unidirectional axial force condition due to high pressure ratio applications. In order to improvement the controllability of AMB system, we designed a magnetic barrier zone in main flux path of permanent magnets to constrain its magnetic flux to make the flux of current coils and the flux of magnets be decoupled. We used static magnetic field analysis to deduce the analytical model of this axial AMB, and verified our idea through hardware implementation. In our experiments, we demonstrated that the axial AMB can work normally with linear quadratic regulator (LQR) controller, and the control current decreases linearly as the axial support weight increasing. This technology can reduce the axial bearing control current of the chiller. Especially for rated operating conditions, it can maintain a small current consumption and improve system performance.

1. INTRODUCTION

Over the past decades, AMB have been widely used in medium-pressure chiller for residential and light commercial air conditioning systems. The biggest advantage over traditional ball bearings is that AMB can make rotating parts run at high speeds without friction. Therefore no additional mechanical lubrication is required, thereby improving the efficiency of the air conditioning systems. Obviously, AMB is particularly suitable for high speed systems because of the mass of rotor under the same driving power will decrease with the rotation speed. In recent years, due to the application of low global warming potential (GWP) refrigerant, R1234ze becomes one of the suitable refrigerants for the alternatives to R134a (Devecioğlu, 2018). The literature shows that R1234ze has 19% lower mass flow rate per unit volume than R134a (Mota-Babiloni, 2016). In other words, compressors using R1234ze refrigerant have a larger specific volume than R134a, resulting in an increase of the impeller size and a decrease in design speed. In our practical experience, using the 250RT compressor as a comparison benchmark, the design speed of a unit using R134a refrigerant is about 18,000rpm. After replacing it with R1234ze and redesigning the impeller, the speed is adjusted downward to 15,500rpm, which is about 14% decrease, which required the design of a more cumbersome driving motor. Due to the international trend of replacing low-GWP refrigerants, the design speed of new compressors may gradually decrease in the future. In view of this, increasing the carrying capacity of AMB is one of the trends in future development, but it is not as necessary condition. In low pressure refrigerant applications, the AMB is not a mainstream bearing technology. Especially in applications above 1,000RT, there are no mature AMB products on the market of low-pressure chiller. Instead, pure refrigerant lubrication (PRL) technology uses refrigerant as the lubricating medium for ceramic ball bearings, becoming the popular application in this field (Morales-espejel, 2022). In the conventional technology, the weight of rotating shaft of the compressor is supported by the radial bearing; the axial bearing provides external force to balance the pressure difference between the inlet and outlet of impellers. As the size of the impellers increase, it can be expected that both the load on the axial and radial bearings will increase. Among them, the radial bearings need to control four degrees of freedom of the rotating shaft, and the control method needs to compensate for gyroscopic effect. Enhancing the load requires must arise the output capabilities of the four sets of radial bearing simultaneously, which will significantly increase the system implementation cost. This is one of the main reasons why AMB technology cannot be extended to low-pressure refrigerant chiller with lager refrigeration tons. When the axis of rotating shaft is changed from horizontal to vertical, the weight of shaft, which was originally carried by the radial AMB, will be supported by the axial AMB only. If we can properly design this axial AMB to overcome the shaft weight, the capacity of the radial AMB will no longer be the limit of the AMB technology with cumbersome shaft. When the increasing mass of the shaft is supported by the axial AMB totally, it is expected that AMB technology could be able to applied to the field of low-pressure chiller with higher refrigeration tons easily. In this study, we will first explain the principle of axial magnetic bearing and deduce the design method of axial AMB with initial magnetic force. Subsequently, through simulation analysis and experimental verification, it was confirmed that this axial AMB has the characteristics of large load capacity and low energy consumption.

2. DESIGN OF AXIAL MAGNETIC BEARING

2.1 Principle of Axial AMB

The traditional axial AMB uses two pairs of coils, which are placed on both sides of the thrust disk. By adjusting the exciting currents of the coils, the direction of the resultant force on the disk is controlled, as shown in Figure 1. Through the displacement sensor (not marked on the picture), the axial displacement of disk is detected. When its position is biased to left side and the controller wants to move the disk toward right, the AMB driver needs to make the current of the coil on the right side increase and at the same time decrease the coil current on the left side. Therefore, the direction of the resultant of magnetic forces on the disk increase toward the right, and vice versa.

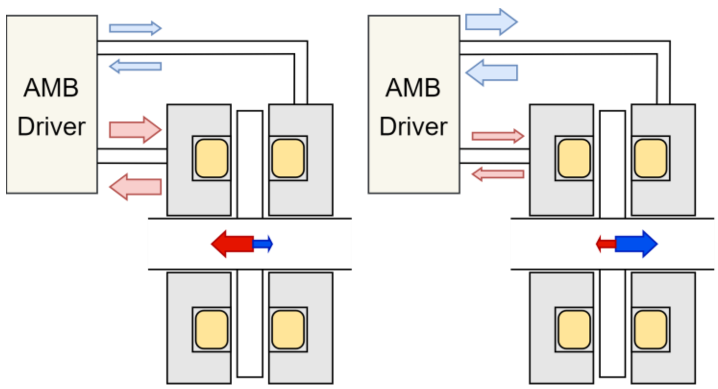

Figure 1: Description of the action behavior of axial AMB

In order to explain more clearly how the axial AMB work, we only consider the electromagnet on one side, as shown in Figure 2. Assume that air gap between thrust disk and electromagnet is g, the number of coil turns is N, and the control current is i_c, the cross-sectional area of air gap is A, under the restriction that its main flux path has not reached magnetic saturation, its resultant of magnetic forces can be given in Equation (1).

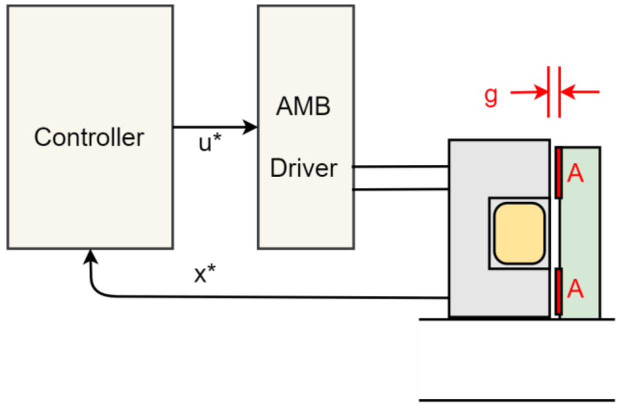

Figure 2: Description of magnetic force between electromagnet and its target

$$F_{mag} = \frac{\mu_0 A N^2}{2} \left(\frac{i_c}{g} \right)^2 \tag{1}$$

Obviously, the magnetic force is proportional to the square of the control current and inversely proportional to the square of the air gap. The control current has a nonlinear relationship with the magnetic force. Generally speaking, the AMB that only has a single-side actuator must use nonlinear theory to achieve its control purpose. Assume that the air gap is much larger than the disk displacement, place the same actuators on both sides of the disk, and divide the input current of the actuator coil into a control current i_c and a bias current i_b, as shown in Figure 3. The resultant of magnetic forces of disk can be described as Equation (2). When the bias current is fixed, its resultant of magnetic forces is linearly related to the control current and the linear control theory can be applied to achieve good control quality.

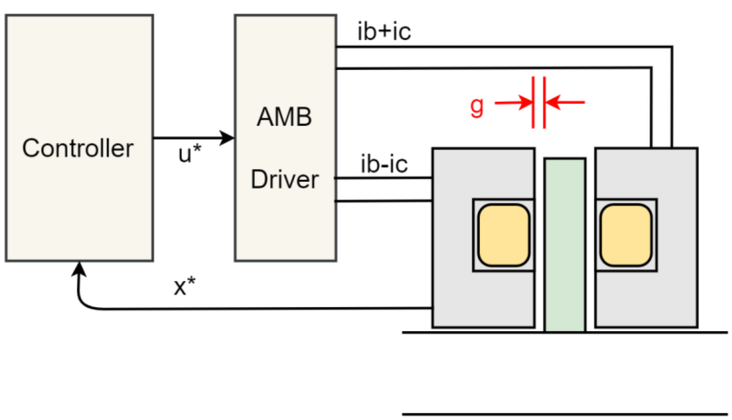

Figure 3: Description of magnetic force of axial AMB

$$\sum F_{mag} = \frac{2\mu_0 A N^2 i_b}{g^2} i_c \tag{2}$$

By observing its physical behavior, in order to achieve the goal of linear control, it is necessary to create destructive and constructive magnetic fluxes on both sides of disk to make the resultant force linearly related to the control current.

2.2 Permanent Magnet Biased Axial AMB

For energy saving, the magnetic flux component generated by the fixed bias current can be replaced by permanent magnets. This structure is widely used in AMB's design for high speed compressors, especially in the design of radial/axial hybrid bearings. The general structure of a radial/axial hybrid AMB with permanent magnets is shown in Figure 4. The blue solid line represents the flux path of the permanent magnet; the red dotted line represents the flux path generated by the exciting current in coils. On both sides of disk, the flux generated by the permanent magnet are equal in magnitude and opposite in direction. Therefore, when it combines with the magnetic flux energized by the coil, it will form destructive and constructive fluxes in both sides of disk. However, when the air gap difference on both sides of the disk is significant, the permanent magnetic flux cannot be regard as equal. A special compensation mechanism needs to be designed to maintain the assumption that the permanent magnetic flux on both sides of disk is fixed (Filatov, 2016). When the aforementioned assumptions are met, it can be inferred that the exciting current of coil is proportional to the resultant of magnetic forces on its disk. When the axial load is heavier, the required exciting current is larger, and its axial load capacity depends on the allowable upper limit of coil of axial AMB. Therefore, in many studies on increasing the load of axial AMB, the one of major problems to be solved is to increase the capacity of coil current, such as improving the heat dissipation of coils. (Yang, 2014)

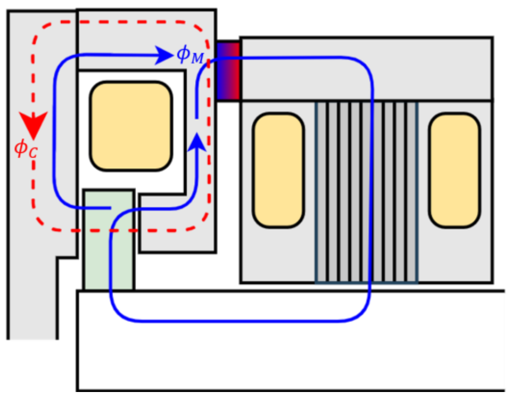

Figure 4: The sketch of radial/axial hybrid AMB

In this paper, we change the position of the permanent magnet as shown as Figure 5. The blue solid line represents the flux path of the permanent magnet; the red dotted line represents the flux path generated by the control current of coil. Compared with Figure 4, the permanent magnetic flux path of this new architecture is limited to the axial AMB only, and effectively simplify the axial AMB structure and can be applied independently. In addition, the shortening of this flux path also increases the bandwidth of axial AMB, overcoming the previous problem of the poor control response (Filatov, 2012). The magnetic resistance of air gap on this permanent magnetic flux path changes with the displacement of the disk. Therefore, it is necessary to design a magnetic saturation zone on this path to limit the change of magnetic flux in order to avoid interfering with the flux of exciting coil current. The air gap of the permanent magnetic flux is on one side of the thrust disk. In other words, the permanent magnets can only provide unidirectional magnetic force to act on the disk. Even without coil current excited, this magnetic force is large enough to carry heavy load and save energy. Obviously, this design has many excellent features and is particularly suitable for applications with large axial loads. The only unresolved problem is that there is no guarantee that the axial bearings of this architecture will have linear characteristics. The design conditions and limitations of this kind of axial AMB can be found through mathematical deduction, and are explained in the remaining sections.

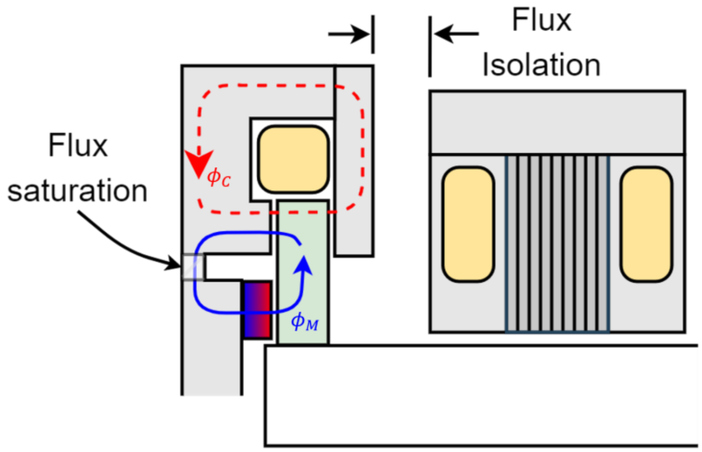

Figure 5: The sketch of axial AMB with high load capacity

2.3 Derivation of Analytical Solution

Assuming that the magnetic fluxes of the axial AMB is isolated from the outside, and no external flux leakage occurs. In addition to the aforementioned magnetic fluxes, there is still a magnetic flux leakage inside the device as shown by the purple dotted line in Figure 6. The above magnetic fluxes pass through three air gaps, and their areas are A_1, A_2, A_3, respectively. The permanent magnetic flux is Φ_M; the flux due to exciting current is Φ_C; the leakage of flux is Φ_L. the magnetic forces generated by the fluxes of air gaps around the disk can be expressed by Equation (3).

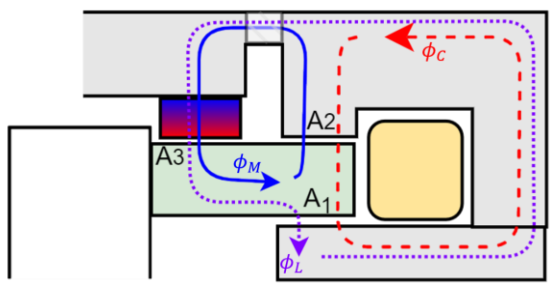

Figure 6: The magnetic flux paths in axial AMB

$$F_1 = \frac{1}{2\mu_0 A_1}(\phi_C + \phi_L)^2$$
$$F_2 = \frac{1}{2\mu_0 A_2}(\phi_M - \phi_C)^2 \qquad (3)$$
$$F_3 = \frac{1}{2\mu_0 A_3}(\phi_M + \phi_L)^2$$

Simplify the areas of air gap to dimensionless parameters λ and λ', as shown in Equation (4)

$$\frac{A_1}{A_2} = \lambda$$
$$\frac{A_1}{A_3} = \lambda' \tag{4}$$

Then the resultant force of disk can be expressed as follow Equation (5):

$$\Sigma F_{mag} = \frac{1}{2\mu_0 A_1}[\lambda(\phi_M - \phi_C)^2 + \lambda'(\phi_M + \phi_L)^2 - (\phi_C + \phi_L)^2] \tag{5}$$

The above equation is further expanded and organized as Equation (6), where Φ_{ctrl} is the magnetic flux related to the coil current, and Φ_{nctrl} is the irrelevant one.

$$\Sigma F_{mag} = \frac{1}{2\mu_0 A_1}(\phi_{ctrl} + \phi_{nctrl})$$
$$\phi_{ctrl} = (\lambda - 1){\phi_C}^2 - 2(\lambda\phi_M + \phi_L)\phi_C \tag{6}$$
$$\phi_{nctrl} = (\lambda + \lambda'){\phi_M}^2 + (\lambda' - 1){\phi_L}^2 + 2\lambda'\phi_M\phi_L$$

To design the dimensionless parameter λ equals to one, so that the resultant force of disk can be linearized. When the permanent magnetic flux Φ_M is designed in the saturation condition, it can be assumed as constant, and the leakage flux Φ_L could be regarded as zero. In other words, the above assumptions satisfy the following equations:

$$A = A_1 = A_2$$
$$\phi_M + \phi_L \cong \phi_M \cong \phi_M - \phi_L = \text{constant} \tag{7}$$

Based on above conditions, the resultant of magnetic forces can be further simplified as shown in Equation (8).

$$\Sigma F_{mag} = \frac{1}{\mu_0 A}\left[\frac{(1 + \lambda')}{2}{\phi_M}^2 - \phi_M\phi_C\right] \tag{8}$$

Obviously, from Equation (8), it can be found that the resultant of magnetic forces on disk is linearly related to the flux of exciting current. Assuming that the air gaps are much larger than displacement of disk, the above equation can be rewritten as follows:

$$\Sigma \mathrm{F}_{mag} = \frac{(1 + \lambda'){\phi_M}^2}{2\mu_0 A} - \frac{\phi_M N}{2g} i_C \tag{9}$$

By making the areas of the air gap related to the exciting flux equal and designing a magnetic barrier at the main path of the permanent magnetic flux path, the resultant of magnetic force on disk can be linearly related to the control current. When no control current energized, the disk is still subjected to an initial magnetic force. After the control current is supplied, the resultant force on the disk gradually decreases as the control current increases, as shown in Figure 7.

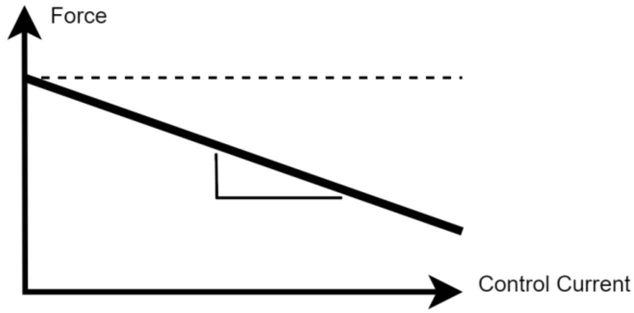

Figure 7: The relationship between resultant force and exciting current

3. Simulation and Experiment

3.1 Simulation for Axial AMB

In order to verify the design concept, our team used the finite element analysis software Maxwell 2D to analyze the axial AMB model. The material of the yoke and disk of this model is SCM435, and the magnet uses NdFeB grade 35. The designed air gap between the yoke and the disk is 0.4mm, and the movement range is 0mm to 0.8mm, so the origin of the disk is defined as 0.4mm; the designed air gap at the junction of both sides of the disk and yoke is equalized, and the magnetic barrier is achieved by reducing the geometric size on the permanent magnet flux path. The results of the finite element analysis are shown in Figure 8. By the magnetic flux distribution of the model's cross-section, it can be confirmed that the magnetic barrier structure is indeed the main path of the permanent magnetic flux and be limited below 2.2T. By adjusting the exciting current from 0A to 2.5A and displacement from 0.1mm to 0.4mm, the parametric analysis was performed to draw the surface diagram of resultants on disk as shown in Figure 8. The analysis results showed that the resultants within this parameter range can be fitted by a plane, verifying that there a linear relationship between the control current and the resultant force. Especially for the disk position at the center (0.4mm), its linearity is better than the off-point (0.1mm). This plane equation can be described as Equation (10) and its coefficients represents the initial axial force, stiffness of displacement and stiffness of coil current with the axial AMB, respectively. We will compare the simulation and experiment results at next section.

$$\Sigma F_{mag} = F_0 - Kx - K_c i_c \tag{10}$$

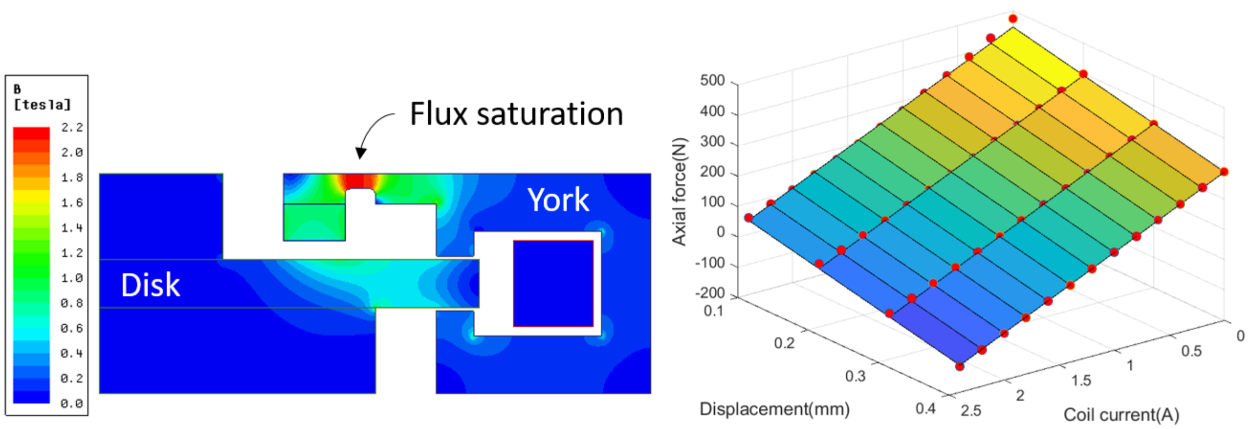

Figure 8: The simulation results of axial AMB

3.2 Experiment of Axial AMB Model

Based on simulation results, our team designed and manufactured a prototype of the axial AMB as shown in Figure 9. In addition to the axial AMB, this experimental model also includes two sets of linear ball bearings to constrain the radial movements. The displacement detector uses a commercially available eddy current sensor (Micro-epsilon eddyNCDT 3005) with a measuring range of 1mm. The experiment used barbell weights to test the load capacity of this model. An oscilloscope was used to record the displacement of disk and the control current. The self-weight of the disk and shaft is 8.43Kg. Experimental results show that this axial AMB can support 15Kg weight form initial position to 0.4mm with LQR controller and the experimental result plotted as shown in Figure 10. In the initial position, this experiment needed to resist the magnetic force on the disk, and the controller must input a large exciting current. Instead, because part of the magnetic force supported the object's weight, only a tiny current was needed to maintain levitation in the equilibrium position. In order to verify the difference between the simulation and actual experiment, we adjusted the weight from 5Kg to 30Kg, the displacement from 0.2mm to 0.6mm, and recorded the coil current when the system reached to steady state. Comparing the experimental and simulation results are shown in the Table 1. This shows that the stiffness obtained from experiment is about 16% lower than the simulation results. The possible reasons are the difference of material properties or controller delay. However, these differences do not affect the practical application of this technology.

Table 1: Difference between simulation and experiment

	Axial Force(N)	**Stiffness of Displacement (N/mm)**	**Stiffness of Coil Current (N/A)**
Simulation Result	497.57	523.25	167.03
Experimental Result	473.23	443.02	140.78

Figure 9: The sketch of experiment model and its setup

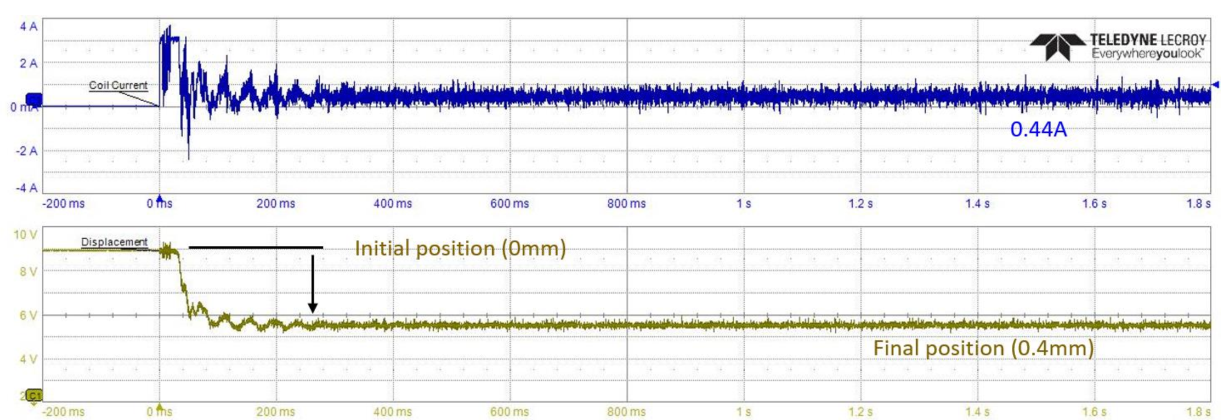

Figure 10: The experimental result by the levitation of 15Kg weight

4. CONCLUSIONS

As the design speed of the compressor decreases, especially for low pressure chiller with large refrigeration tons, magnetic levitation is no longer the mainstream technology in the market. However, to pursue silence and efficiency, applying AMB to this unit is still the market's primary goal. In this study, we proposed a concept of using axial AMB to support the weight of the rotating shaft and impeller to simplify the controller complexity and hardware requirements. Furthermore, we developed an axial AMB design method that uses permanent magnets to support the weight of the rotating shaft to reduce system energy consumption. In order to achieve the goal of linear control, the air gap areas on the exciting flux path are designed to be equal, and a magnetic barrier is designed in the permanent magnetic flux path. Through simulation analysis and experimental verification, it was confirmed that the axial AMB has the ability to carry heavy loads, and its exciting current has a linear relationship with the resultant of magnetic forces. The large axial force requirement may come from the pressure difference between the inlet an outlet of impeller, or the self-weight of the rotating shaft. Regardless of whether the rotating shaft is placed horizontally or vertically, this novel axial AMB structure is expected to expand the application fields of magnetic levitation technology in centrifugal compressors.

NOMENCLATURE

μ_0	vacuum permeability
A	area of air gap
N	number of coil turns
g	air gap
i	coil current
F	force on thrust disk
ΣF	resultant of forces
Φ	magnetic flux
λ	dimensionless area ratio
K	stiffness of AMB

Subscript

0	initial value
b	based
c	controlled
mag	magnetic
M	permanent magnet
C	exciting coil
L	leakage
ctrl	controllable
nctrl	non-controllable

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