

# Research on the Equivalent Friction Force and Power Loss of a Magnetic Bearing

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## Abstract

Compared with rolling bearing and sliding bearing, there is no mechanical friction and wear in magnetic bearing because there is no mechanical contact. But there is still a similar character with the mechanical friction force while magnetic bearing working. The force can be defined as an equivalent friction force for the similar to mechanical friction force. The equivalent friction force is studied and is used in calculation of power loss in magnetic bearing. It means that the power loss in magnetic bearing is equal to the equivalent friction force multiplied by the rotor speed. The definitions of the power loss in magnetic bearing and friction character are the same as those of rolling bearing and sliding bearing. A research method of equivalent friction force and power loss in magnetic bearing which is analogy of the conventional research method of rolling bearing and sliding bearing is put forward. A calculation method of power loss in magnetic bearing is presented. All of this will benefit the design of magnetic bearing system.

## 1 Introduction

Magnetic bearing is a special form of the bearing which makes its rotor suspend in space using a controllable electromagnetic force. Because of its many unique characteristics, such as un-contact, no abrasion, lubrication free, long lifetime, fitting for high speed and controllable etc. the magnetic bearing has a wide application in many areas. The magnetic bearing eliminates mechanical friction, but due to exists of magnetic field there is still a character which is similar with the mechanical friction force while the magnetic bearing working. The force can be defined as the equivalent friction force for the similar to mechanical friction force. In addition, there is the windage loss while the rotor working.

Paper [1] indicates that the power loss of magnetic bearing rotor system mainly result in windage loss and iron loss, and iron loss of its rotor can be divided into by eddy current loss, alternating hysteresis loss and rotational hysteresis loss. Paper [2] introduces a method to get an analytic power loss solution for the laminated rotors of a homopolar magnetic bearing, and verifies the veracity of the result by contrasting experimental data. The paper [3] analysis the power loss of paired pole arrangement (NNSS) and alternating pole arrangement (NSNS) with experimental method, and it found that the power loss of paired pole arrangement (NNSS) was smaller than the loss of alternating pole arrangement (NSNS) when it's experiments are at high speeds and high flux densities. The paper [4] shows that the power loss of paired pole arrangement (NNSS) is 1.5 power of the speed of levitated Rotor, and it is proportional to the square root of number of the pole. However, the paper [5] shows that the rotor power loss of paired pole arrangement (NNSS) changes as the rotor speed, the levitation gap and the magnetic flux density change, and it is irrelevant to the number of poles. The paper [6] utilizes a magnetic levitation platform as the object of study and measured so called "electromagnetic friction" with experimental method, the order of magnitude measured "electromagnetic friction" coefficient is  $10^{-2}$ . But the paper does not indicate the principle of electromagnetic friction as well as how to calculate the electromagnetic friction. The paper [7] points out that order of magnitude of superconducting magnetic bearings friction coefficient is  $10^{-7}$ , while order of magnitude of electromagnetic bearings friction coefficient is  $10^{-4}$ . However, there is a huge discrepancy between the paper [6] and the paper [7].

This research aims to research the equivalent friction force and the power loss of the magnetic bearing rotor. In order to make the research more universal meaning, the magnetic bearing is simplified into the minimum unit, U-type magnetic bearing, and the magnetic experimental system is simplified into the two degrees of freedom of magnetic bearing apparatus with two U-type electromagnets. The equivalent friction force and the power loss of the rotor from a specific structure of the two degrees of freedom of magnetic levitation apparatus is analyzed with experimental method and analysis method, and some significant conclusions are obtained.

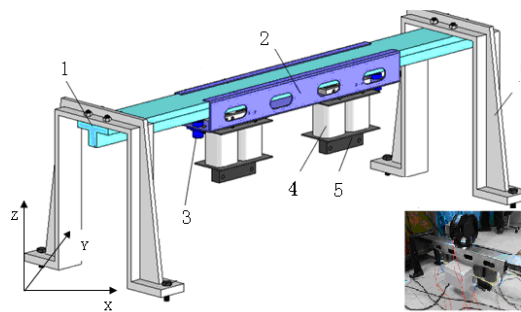
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## 2 Experimental Device Design Principles

For magnetic bearings no matter how many different types or structures, they can be simplified into U-type electromagnet. For instance 8-pole radial magnetic bearing can be simplified as four U-type electromagnets uniformly distributing along the circumferential, while axial bearing can be simplified as one U-type electromagnet that distributes along a centerline of rotation.

In the paper two degree of freedom of magnetic levitation experimental apparatus is designed basing on U-type electromagnet. The experimental apparatus is shown in Figure 1. The moving object consists of two U-type electromagnets. The stator is support frame rail.



1-support frame rail; 2- the moving object ; 3-sensor ; 4-coil; 5-U-type electromagnet; 6- support frame

Figure 1: Diagram of the device structure

The working principle of the system is as shown in Figure 2, in the thinking of reducing the interaction of various factors and simplifying the structure.

The X axial dimension is decreased in mechanical structure in order to reduce one degree of freedom, i.e. ignoring the rotational degree of freedom around the Y axis of the suspended object. Use two magnetic bearings to constraint two degrees of freedom that rotation and movement along the Z axis. Use the centripetal effects to constraint the movement along the X axis and the rotational degree of freedom around the Z axis. Movement along the Y axis is not constrained [8,9].

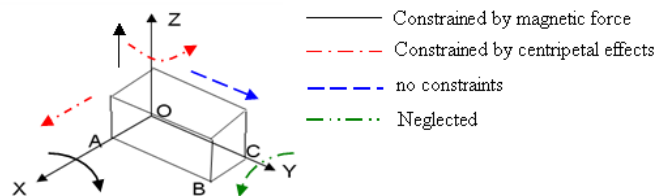


Figure 2: Schematic diagram of the device

## 3 Experimental Method

The experimental procedure is as follow: the moving object is magnetic suspended steady on the rail; tilted the rail and put the moving object onto the peak of tilted rail; release the moving object and let it slide down freely under the action of the gravity. Due to the speed of the moving object does not exceed 0.7m /s the windage loss is negligible [10]. The equivalent friction force  $F_z$  caused by the magnetic field of U-type electromagnets which resistant the moving object from moving can be calculated by equation (1). The mechanics analysis of the moving object in the tilt rail is shown in Figure 3.

$$F_z = mg \sin \alpha - ma \tag{1}$$

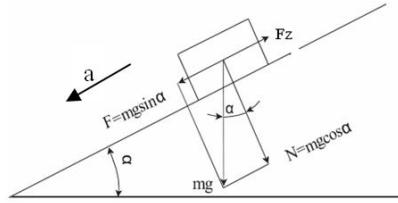


Figure 3: Measurement theory diagram for the equivalent friction force

Here  $F_z$  is the equivalent friction force measured by experimental methods;  $m$  is quality of the moving object;  $g$  is acceleration of gravity;  $\alpha$  is tilt angle of the rail;  $a$  is acceleration of the moving object.

According to equation (1), the equivalent friction force can be calculated if the acceleration of the moving object is measured. The image of the moving object is taken with a 24 frames/s camera in the experiment. The displacement, velocity, acceleration of the moving object can be got through Avimeca2.7 software. The power loss of the moving object can be got through the equation (2).

$$P_z = F_z v \tag{2}$$

Here  $P_z$  is the power loss of the moving object;  $v$  is velocity of the moving object.

### 3.1 The Levitation Gap Effects

Before the equivalent friction force of the moving object is experimental measured for three levitation gaps: 1.2mm, 1.6mm, 2.0mm, the bias currents of three experiments are set to 1.5A, and the rail tilt angle are  $0.0317^\circ$ . Figure 4 shows the moving object's distance and time for three levitation gaps. Figure 5 shows the equivalent friction force of the moving object and its speed for three levitation gaps, and Figure 6 shows the power loss of the moving object and its speed for three levitation gaps.

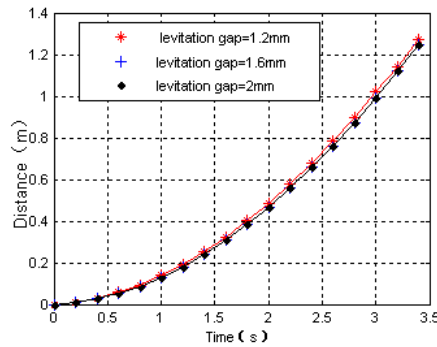


Figure 4: The moving object's distance vs. time for three levitation gaps

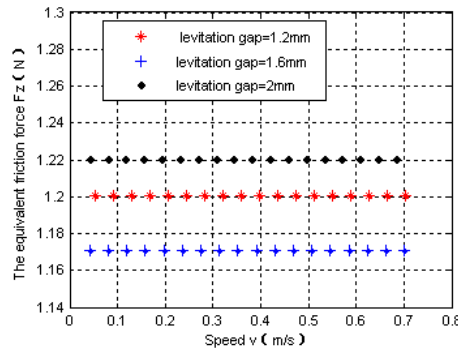


Figure 5: The equivalent friction force of the moving object vs. its speed for three levitation gaps

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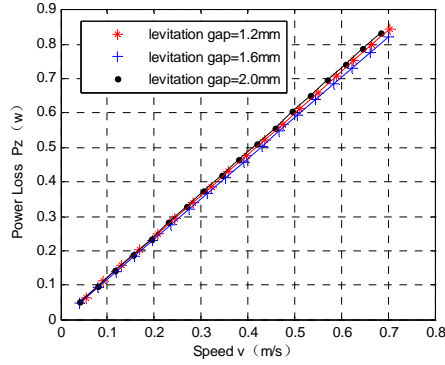


Figure 6: The power loss of the moving object vs. its speed for three levitation gaps

To verify the above analysis, the currents of the U-type electromagnets in the whole process are collected using current sensors. Figure 7 shows the currents of U-type electromagnets and time with levitation gap at 1.2mm. Figure 8 shows the currents of U-type electromagnets and time with levitation gap at 1.6mm. Figure 9 shows the currents of U-type electromagnets and time with levitation gap at 2.0mm.

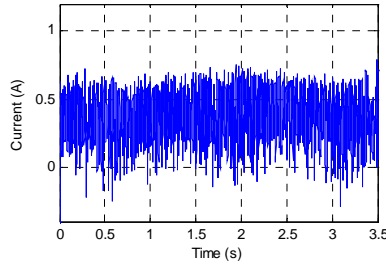


Figure 7: Current of U-type electromagnets vs. time with levitation gap at 1.2mm

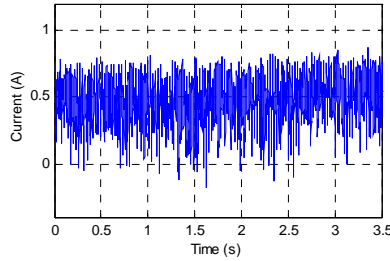


Figure 8: Current of U-type electromagnets vs. time with levitation gap at 1.6mm

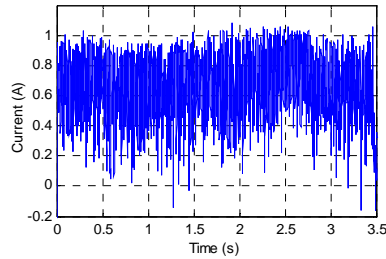


Figure 9: Current of U-type electromagnets vs. time with levitation gap at 2.0mm

According to the collected currents, the average of the currents can be obtained for three levitation gaps, and the average magnetic flux densities can be calculated using Equation 3. The average currents and the average magnetic flux densities of the U-type electromagnets are shown in Table 1.

$$B_a = \frac{Ni_a \mu_0}{2s} \tag{3}$$

Here  $i_a$  is the average current in the U-type electromagnet;  $B_a$  is the average magnetic flux density; N is number of coil;  $\mu_0$  is vacuum permeability; s is levitation gap.

levitation gaps(mm)	1.2	1.6	2.0
$I_a$ (A)	0.4467	0.5602	0.7445
$B_a$ (T)	0.3507	0.3299	0.3514

Table 1: The average currents and the average magnetic flux densities for three levitation gaps

Compared with the equivalent friction force and the power loss of the moving object for three levitation gaps from Figure 5 and Figure 6, it is obtained that the minimum value of the equivalent friction force and the power loss are appeared at the levitation gap 1.6mm. And compared with the average magnetic flux density of U-type electromagnets for three levitation gaps from Table 1, it is also obtained that the minimum value of the magnetic flux density is appeared at the levitation gap 1.6mm.

### 3.2 The Bias Current Effects

Before the equivalent friction and the power loss of the moving object is experimental measured for three average bias currents: 1.3A, 1.5A, 1.7A. The levitation gaps of three experiments are set to 1.4mm, and the rail tilt angle are  $0.0317^\circ$ . Figure 10 shows the moving object's distance and time for three bias currents. Figure 11 shows the moving object's equivalent friction and its speed for three bias currents, and Figure 12 shows the moving object's power loss and its speed for three bias currents.

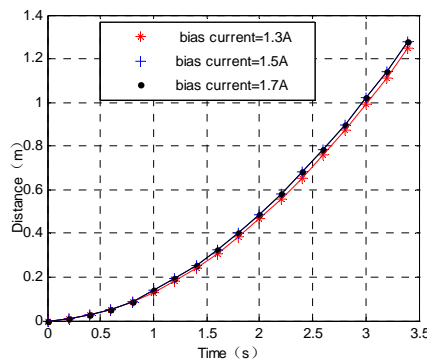


Figure 10: The moving object's distance vs. time for three bias currents

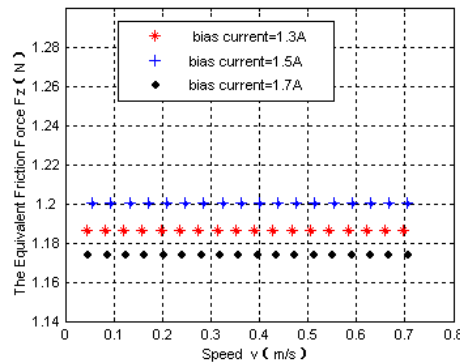


Figure 11: The moving object's equivalent friction vs. speed for three bias currents

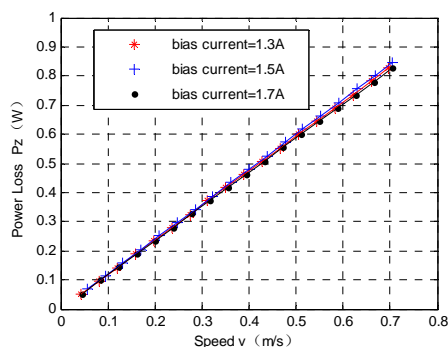


Figure 12: The moving object’s power loss vs. speed for three bias currents.

The average currents and the average magnetic flux densities of the U-type electromagnets for three bias currents are obtained using above method , and they are shown in Table 2.

Bias Currents(A)	1.3	1.5	1.7
$I_a(A)$	0.5194	0.5235	0.5190
$B_a(T)$	0.3494	0.3522	0.3488

Table 2: The average currents and the average magnetic flux densities for three bias currents

Compared with the equivalent friction force and the power loss of the moving object for three bias currents from Figure 11 and Figure 12, it is obtained that the minimum value of the equivalent friction force and the power loss are appeared at the bias current 1.7A, and compared with the average magnetic flux densities of U-type electromagnets for three bias currents from Table 2, it is also obtained that the minimum value of the magnetic flux density is appeared at the bias current 1.7A.

In summary, compared with the power loss of U-type electromagnets for different levitation gaps, the minimum power loss is not appeared in the smallest levitation gap, but appeared in the smallest magnetic flux density. Compared with the power loss of U-type electromagnets for different bias currents, the minimum power loss is not appeared in the smallest bias current, but appeared in the smallest magnetic flux density. To explain this phenomenon, this paper will establish the analytic model of the moving object’s equivalent friction force and its power loss in the low speed.

## 4 The Analytic Model of Equivalent Friction Force and Power Loss

### 4.1 The Analytic Model

The power loss of the moving object are the sum of four components: eddy current loss, alternating hysteresis loss, rotational hysteresis loss and windage loss. Because two U-type electromagnets can be transformed into a 4-pole radial magnetic bearing, and the linear motion of the moving object can be converted to the rotation of the radial magnetic bearing rotor, the power loss of the moving object is calculated using the power loss equation of radial magnetic bearing rotor, It is shown in Figure 12 that two U-type electromagnets can be transformed into a 4-pole radial magnetic bearing.

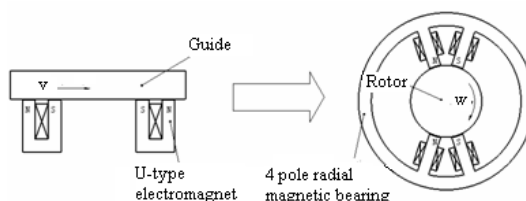


Figure 12: Curve of the transformation between U-type electromagnets and 4-pole radial magnetic bearing

Because the speed of the moving object does not exceed 0.7m/s, its windage loss is ignored, and the power loss can be expressed as<sup>[1]</sup>:

$$P_1 = P_e + P_{hr} + P_{ha} \quad (4)$$

Here  $P_e$  is eddy current loss;  $P_{hr}$  is alternating hysteresis loss;  $P_{ha}$  is rotational hysteresis loss.

According to the definition of the equivalent friction force, the equivalent friction force of the moving object is caused by eddy current loss, alternating hysteresis loss and rotational hysteresis loss, so it can be expressed as:

$$F_1 = \frac{P_1}{v} \quad (5)$$

A equation for eddy current loss of the laminated radial magnetic bearing can be expressed as<sup>[11]</sup>:

$$P_e = K_e f^2 B^2 V \quad (6)$$

A equation for alternating hysteresis loss and rotational hysteresis loss of the laminated radial magnetic bearing can be expressed as<sup>[11]</sup>:

$$P_{ha} = k_{ha} f B^{1.6} V \quad (7)$$

$$P_{hr} = n k_{hr} f B^{1.6} V$$

Here  $f$  is the effective frequency;  $B$  is the flux density,  $k_e$  is eddy current loss coefficient;  $k_{ha}$  is alternating hysteresis loss coefficient;  $k_{hr}$  is rotational hysteresis loss coefficient;  $V$  is effective volume,  $n$  is the number of  $N$ ,  $S$  alternating when the rotor rotates a full circle.

The equivalent friction force and the power loss of the moving object can be expressed as Equation (8) according to the Equation (4)-(7):

$$P_1 = K_e f^2 B^2 V + k_{ha} f B^{1.6} V + n k_{hr} f B^{1.6} V \quad (8)$$

$$F_1 = \frac{K_e f^2 B^2 V + k_{ha} f B^{1.6} V + n k_{hr} f B^{1.6} V}{v}$$

Eddy current loss coefficient, alternating hysteresis loss coefficient, rotational hysteresis coefficient and effective volume for the structure of the moving object do not change as the levitation gap changing or the bias current changing, so the equivalent friction force and the power loss of the moving object is only associated with the magnetic flux density  $B$  of the U-type electromagnets. They increase as  $B$  increases, and they decrease as  $B$  decreases to explain the experimental phenomena.

## 4.2 The Analytic Calculation

Before the calculated equivalent friction force and the calculated power loss is obtained, the magnetic flux density of two U-type electromagnets is calculated. Because the electromagnetic force of two U-type electromagnets is equal to the gravity of the moving object, the equation can be expressed as:

$$F = \frac{B_1^2 A}{\mu_0} = \frac{mg}{2} \quad (9)$$

Here  $F$  is the electromagnetic force of single U-type electromagnet;  $B_1$  is the magnetic flux density with analytic method;  $A$  is pole area of single U-type electromagnet.

According to Equation (9), the calculated magnetic induction  $B_1$  is equal to 0.3101T, and the equivalent friction force and the power loss are the same for different levitation gaps or different bias currents with analytic method.

When the levitation gap equal 1.2mm and the bias current equal 1.5A, the calculated equivalent friction force is shown in Figure 13, and a breakdown of the components of the calculated power loss is shown in Figure 14.

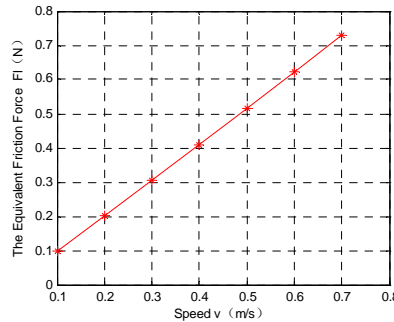


Figure 13: Calculated equivalent friction force vs. speed with levitation gap at 1.2mm and the bias current at 1.5A

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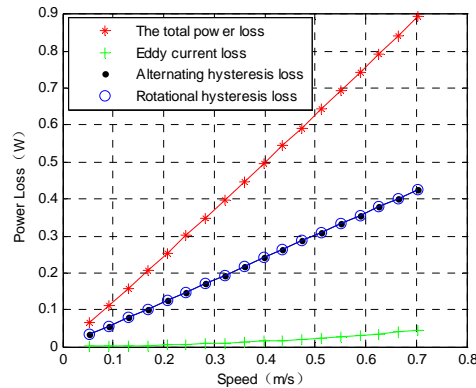


Figure 14: Calculated power loss components vs speed with levitation gap at 1.2mm and the bias current at 1.5A

According to Figure 14, the sum of alternating hysteresis loss and rotational hysteresis loss is more than 90 percent of the total power loss when the velocity of the moving object is less than 0.7m/s with the levitation gap at 1.2mm and the bias current at 1.5A, however eddy current loss is less than 10 percent of the total power loss, so the power loss of the moving object mainly comes from hysteresis loss when the velocity of the moving object is less than 0.7m/s.

## 5 Discussion

The paper compares the analysis solution with the measured value of power loss as follows: the error between of them is given by Equation (10):

$$\varepsilon_2 = \frac{P_z - P_1}{P_z} \times 100\% \tag{10}$$

Table 3 and Figure 15 show the comparison of the analysis solution with the measured value of power loss.

Speed (m/s)	0.1	0.3	0.5	0.7
$P_1$ (w)	0.100	0.304	0.514	0.729
$P_z$ (w)	0.120	0.360	0.600	0.840
Error	16.7%	15.6%	14.3%	13.2%

Levitation gap 1.2mm and the bias current 1.5A.

Table 3: Analysis solution and measured value of power loss

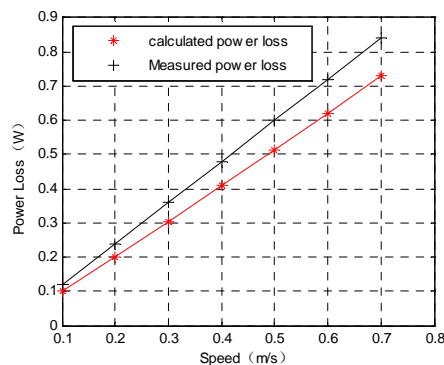


Figure15: Analysis solution and the measured value of power loss with the levitation gap at 1.2mm and the bias current at 1.5A

According to the analysis above, there is 16.7 percent maximum error between the analysis solution and the measured value of power loss when the velocity of the moving object is less than 0.7m/s with the levitation gap at 1.2mm and the bias current at 1.5A. The error of the power loss mainly comes from the error of the magnetic flux density. According to Equation (8), the power loss is quadratic polynomial of the magnetic flux density, if the



calculated magnetic flux density  $B_l$  is a little different from the measured magnetic flux density  $B_a$ , there will be a greater error between the analysis solution and the measured value of power loss.

If the power loss is obtained by substitute the measured magnetic flux density  $B_a$  into formula (8) as showed in Table 4. The maximum error is -6.23 percent.

Speed (m/s)	0.1	0.3	0.5	0.7
Pw (w)	0.122	0.371	0.628	0.893
Pz (w)	0.120	0.360	0.600	0.840
Error	-1.4%	-2.93%	-4.58%	-6.23%
Levitation gap 1.2mm and the bias current 1.5A				

Table 4: The power loss by substitute the measured magnetic flux density  $B_a$  into Equation (8)

## 6 Conclusions

- There is 16.7 percent maximum error between the analysis solution and the measured value of power loss when the velocity of the moving object is less than 0.7m/s with the levitation gap at 1.2mm and the bias current at 1.5A. That declares that the calculated magnetic flux density with magnetic suspended quality is not acceptable. The magnetic flux density can not be calculated with magnetic suspended quality for the magnetic levitation system with differential control so that the power loss also can not be calculated.
- The analysis solution and the measured value of power loss of the moving object are approximately linear with the velocity when the velocity of the moving object is less than 0.7m/s. This is because the power loss of the moving object mainly comes from hysteresis loss, and hysteresis loss is linear with the velocity.
- Compared with the power loss of U-type electromagnets for different air gaps, the minimum power loss is not appeared in the smallest air gap. But appeared in the smallest magnetic flux density. Compared with the power loss of U-type electromagnets for different bias currents, the minimum power loss is not appeared in the smallest bias current. But appeared in the smallest magnetic flux density.
- The above conclusions are only suitable for low-speed movement of magnetic bearing.

## 7 Acknowledgement

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