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# DESIGN AND REALIZATION OF MAGNETIC SUSPENDED DEVICE BASED ON EDGE EFFECT

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**ABSTRACT**
Edge effect is neglected in most of the research and application of active magnetic bearing (AMB) because it is much smaller than main magnetic. Based on the analysis of edge effect of the magnetic bearing, designed and developed a magnetic suspended device based on edge effect, established mathematics model of control for magnetic suspended disk, proposed a decoupling control arithmetic and designed both hardware and software. By system debugging on machine, the result shows that the device has not only the stability of magnetic suspended disk, but also good performance of dynamic and static characteristics. Thus, applying edge effect in the application of magnetic bearing may simplify system and save cost.
**KEY WORDS:** Edge Effect, Decoupling Control, Magnetic Suspended Disk, PID Controller.

## INTRODUCTION

The inventing of magnetic bearing has brought a completely new concept for bearing technology, its prominent performance is in the two aspects that there is no mechanical contact and it can achieve active control [1], these two notable advantages have immediately aroused people's concern and attention on magnetic levitated technology research. Presently the maglev technology is gradually beginning to be used in man-made satellites, submarines, fighting vehicles and other weapons in the attitude control and energy storage, as well as high-performance turbine, vacuum pumps, centrifugal pumps, generators, compressors, machine tool spindle, nuclear industry, aerospace industry, military equipment and other fields[2][3][4].

According to the feature of its working mode and structure characteristics, maglev technology is mainly applied in two fields: One is for rotating movement, such as machine tool spindle, generators, etc; the other is linear motion, such as maglev train, maglev hard disk, etc. Because active magnetic bearing is an open-loop unstable system, it must be actively controlled in order to normal operation of AMB. The control system is complex in design, high in price and so on, which restrict the applying of AMB. In order to reduce the cost of control system, some degrees of freedom are suspended by the applying of edge effect.

Based on the analysis of edge effect of the magnetic bearing, designed and developed a magnetic suspended device based on edge effect, established mathematics model of control for magnetic suspended disk, proposed a decoupling control arithmetic and designed both hardware and software. By system debugging on machine, the result shows that the device has not only the stability of magnetic suspended disk, but also good performance of dynamic and static characteristics. Thus, applying edge effect in the application of magnetic bearing may simplify system, save cost and enlarge application fields. The result of project can be applied to research of maglev hard disk, maglev table and so on.

## ANALYSIS OF EDGE EFFECT

Because there have edge flux in each end region of AMB, it has edge effect own to the extending of gap flux. The edge effect is much less than the mainly magnetic force, so it can be neglected in most research and application of AMB. But, in some conditions the force which edge effect produces is used to suspend control object, reduce position sensor, control hardware and so on, simply mechanical structure and control system, in order to save cost.

Figure 1 shows a maglev ball system with the principle arrangement of ball (1), coil (2), electromagnet (3), and air (4). The mass of ball is 28g, coil turn is 2400, offset position is 15.5mm, offset current is 1.2A.

The electromagnet is round bar. A controller is used to control the vertical degree of freedom of ball; two translational degrees of freedom are not need to control. Because of the result of edge effect, the ball can return back to the original position with the certain wind force or other disturbance of translational direction.

With the FEA software ANSYS the magnetic field distribution can be got, as the Figure 2 and Figure 3 show.

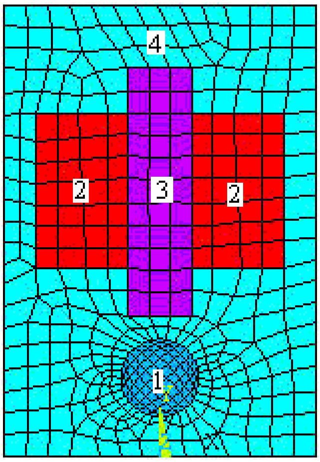


**FIGURE 1:** Maglev ball system

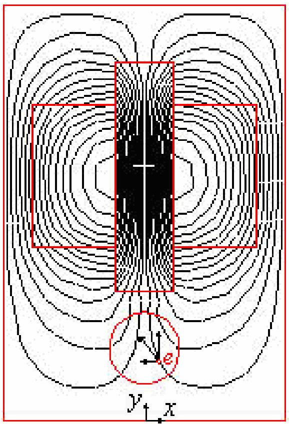


**FIGURE 2:** No eccentric of small ball

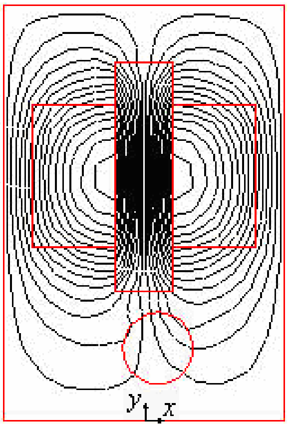


**FIGURE 3:** Right eccentric of small ball

According to Figure 2, analyzing unit force for a small unit (e) in the ball, obviously, unit force $F_e$ is tangent to magnetic line of force, the direction is pointing to electromagnet. According to force decomposition, the force of $x$ axis and $y$ axis is respectively $F_{ex1}$、$F_{ey1}$, so the left and right resultant force in $x$ direction is given by:

$$\begin{cases} F_{xLeft} = \sum_{i=0}^{NL} F_{exi} \\ F_{xRight} = \sum_{i=0}^{NR} F_{exi} \end{cases} \quad (1)$$

Where: *NL*-the number of units in axis Left. *NR*- the number of units in axis right.

As the Figure 2 shows, when the ball and electromagnet have a same axis, achieved $F_{xLeft}=F_{xRight}$. As the Figure 3 shows, when the ball is far from the axis of electromagnet along right, got $F_{xLeft}<F_{xRight}$, namely the resultant force of left and right is not zero, the direction is pointing to left. So the resultant force acts on ball, the ball returns to axis position. The ball is far form left which is same.

Use a line to suspend the ball (Not magnetic bearing), blower generated wind force , the distance between ball and blower is x, wind force is F in level, experimental principle is reference [5]. The experiment result shows in Figure 4.

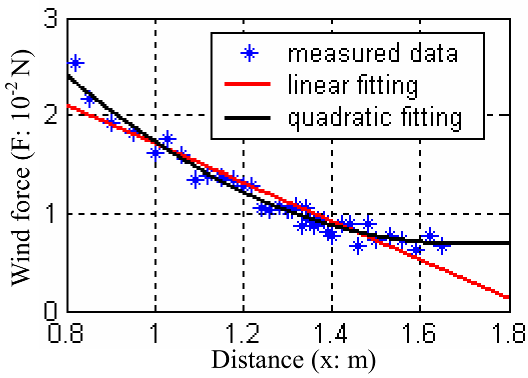


**FIGURE 4:** Fitting curve of wind force

The linear fitting equation is given by:

$$F = -1.976x + 3.686 \quad (2)$$

The quadratic fitting equation is given by:

$$F = 2.118x^2 - 7.22x + 6.832 \quad (3)$$

Firstly, the stable suspension of maglev ball system is achieved, and then blower worked, the ball drop off when the distanceis 1.04m between blower and ball. So, according to the equation (2), $F$=1.631×10$^{-2}$N; according to the equation (3), $F$=1.614×10$^{-2}$N. The main magnetic force is 2.74×10$^{-1}$N.

Obviously, the resultant force by edge effect is small; it's one-seventeenth of the main magnetic force. So, edge effect can be used under special circumstances, this simplifies system and saves cost.

The following conclusions can be drawn, because of existing edge uneven area in AMB, arrangement of magnet line is not uneven in medium. When ball is moving, the force of translational direction equals to resultant force which all magnet lines in uneven area generate. This is producing mechanism which there has edge effect in AMB.

In order to validate existing of edge effect in AMB, ball instead of a certain thickness disk, electromagnet is u-structure. Figure 5(A) and (B) are magnetic line and electromagnetic force distribution obtained with ANSYS software. In the circumstance that the disc has no eccentric in the horizontal direction in Figure 5 (A) and (B), and Figure 5 (C) and (D) with eccentric. It can be seen that, when there is no eccentric disc, the left and right magnetic poles have the same magnetic line distribution, and the component force in the horizontal direction are of the same size, the opposite direction, so the resultant force is zero. When received interference in the right horizontal direction, the right level of discs will offset some distance. As shown in Figure 5 (C). It can be seen, the left and right magnetic pole line distribution are different, and besides vertical main suction, the U-shaped structure will produce a horizontal direction resultant force, as shown in Figure 5 (D), this consultant force is of the opposite direction with the interference, therefore make the disc return to its original position. So, when the horizontal interference is not too big, we can carry out no control.

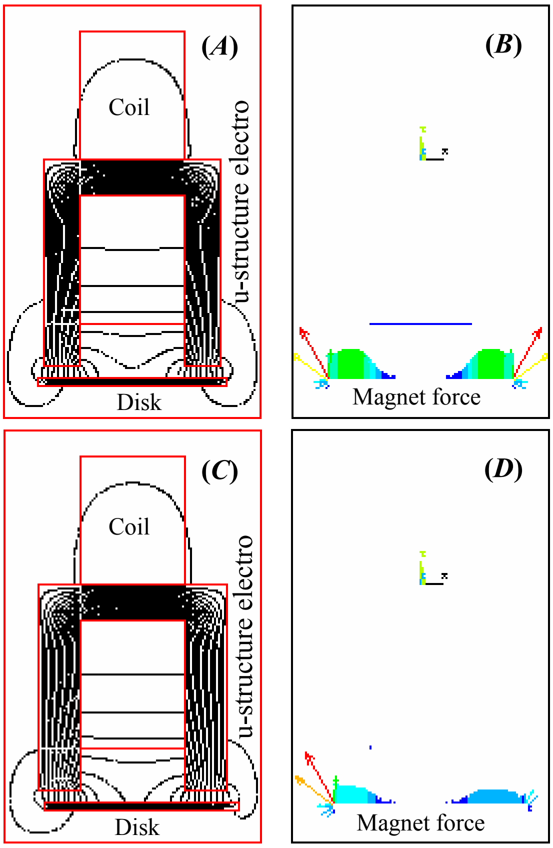


**FIGURE 5:** edge effect of disk analysis

When suspending of the maglev disk is stability, there is no external force in radial direction, so there is no need to control. But when it is leaned or interfered with smaller force (such as the breeze, blowing, etc), the disc will be in horizontal movement, the control of the horizontal direction is to make the magnetic bearing returning to its original location by its edge effect.

## SYSTEM COMPOSITIONS AND WORK PRINCIPLE

Based on edge effect, designed and manufactured a magnetic suspended device, it is composed of three major parts: mechanical, electrical and control software. The mechanism part contains the disk (control object of the whole control system), electromagnet, displacement sensors and cabinet, etc; electrical part contains position signal process unit, regulation control unit and power amplifier, etc. Control software primarily generates the control signal according to the warp between the given signal and the location of the actual disk; consequently make the disk suspends stability in a given location. The physical structure of magnetic suspended device is shown in Figure 6. Hence to make the disk on a fixed position in space, three single-freedom magnetic bearings are needed to achieve stability levitation of the disk, the schematic diagram of system structure is shown in Figure 7.

**FIGURE 6:** Magnetic suspended device

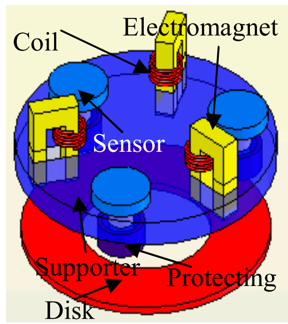


**FIGURE 7:** Schematic diagram

Know from Figure 7, magnetic suspended disk is a three point supported device. When the disk is working, the suspending disk departs from work equilibrium position with outside interference, displacement sensor detect the disk's movement offset signal, through some decoupling control algorithm, can obtain the centre electromagnet's displacement, the controller calculate the control signal with a certain control algorithm, according to the movement maglev disc's offset signal detected by the displacement sensors, then the power amplifier transform this control signal into control voltage or current and carry out active control to the three electromagnets, adjust the disk, make it return to equilibrium position, so as to suspend stably in a given position.

## CONTROL MATHEMATICAL MODEL OF MAGNETIC SUSPENDED DISK

Generally, maglev systems work with differential excitation mode, and here magnetic suspended disk adopts a unilateral approach excitation, the other side adjusts by its own gravity. When the system is working in the equilibrium position, suppose the offset between the disk and electromagnet is $z_{0i}$ ( $i$=1,2,3 ), the working bias current is $I_{0i}$, assume the displacement is $z_i$, control current is $i_{ic}$, set the disk center as the origin of the coordinate, z-axis straight out in the paper, x and y direction are shown in Figure 8.

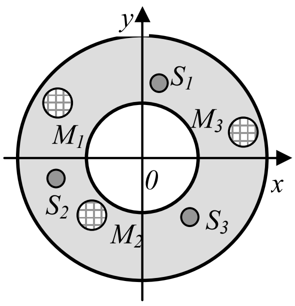


**FIGURE 8:** schematic diagram of arbitrary distribution

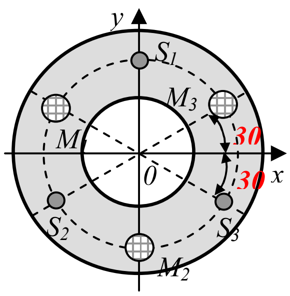


**FIGURE 9:** schematic diagram of the final layout

Take a certain degree system of the magnetic suspended disk as the research object, study by the reference [1] and [2], make the displacement Z as the output, current $I_c$ as the input, the transfer function model can be obtained:

$$G(s)=\frac{Z(s)}{I_c(s)}=\frac{\dfrac{\mu_0 N^2 A I_0}{2z_0^2}}{ms^2-\dfrac{\mu_0 N^2 A I_0^2}{2z_0^3}} \quad (4)$$

where: $_0$=4π×10$^{-7}$$Vs\ Am$, is the relative magnetic conductivity in the vacuum; $N$ is the coil turns; $A$ is the pole area ($m^2$); $I_0$ is the bias current ($A$).

It can be seen from Figure 7, the disc position detected by the sensor is not the electromagnet gap, which requires to be transformed into the electromagnet gap, besides, adopt centralized control to these three channels, so as to ensure the disk takes on good stable suspension effect. To achieve centralized control, it needs to get the physical location of the disk by decoupling according to the value of the three displacement sensors, next let's get some detailed discussion of this content.

Assume the three displacement sensors and the three electromagnets are in a plane above the disk, the displacement sensor location coordinates can be set separately as $S_1$ ($x_{11}, y_{11}, z_{11}$)、$S_2$ ($x_{12}, y_{12}, z_{12}$)、$S_3$ ($x_{13}, y_{13}, z_{13}$) , the coordinates of the three electromagnet are separately: $M_1$ ($x_{21}, y_{21}, z_{21}$)、$M_2$ ($x_{22}, y_{22}, z_{22}$) 和 $M_3$ ($x_{23}, y_{23}, z_{23}$) ,This is undoubtedly the general. Due to the relationship between the work method and machining precision, assembly error, displacement sensor dead zone varying etc, these six points are generally not in the same plane, but through z coordinates translation, which is to add or plus an constant respectively in the six points' z direction, can ultimately ensure that these six points in a plane. when the disk is suspending, the reference position is relative, the given value of the position of disk may not be the same, so the above process is feasible.

According to the three points equation in the plane in higher mathematics, the $S_1$, $S_2$and $S_3$ plane equation is:

$$A(x-x_{11})+B(y-y_{11})+C(z-z_{11})=0 \quad (5)$$

Where:

$$\begin{cases} A=(y_{11}-y_{12})(z_{11}-z_{13})-(y_{11}-y_{13})(z_{11}-z_{12}) \\ B=(x_{11}-x_{13})(z_{11}-z_{12})-(x_{11}-x_{12})(z_{11}-z_{13}) \\ C=(x_{11}-x_{12})(y_{11}-y_{13})-(x_{11}-x_{13})(y_{11}-y_{12}) \end{cases}$$

As sometimes the height of the sensor and the electromagnet are not in the same plane, it can be made in the same plane through a certain translation, Once mechanical structure designing and machining are completed, the coordinate of the sensors and electromagnets in the x and y direction is decided. Therefore, according to the actual measured values of displacement sensor, calculate the actual location of corresponding electromagnet's centre, and thus control the magnetic suspended disk suspend stably.

Assume $M_1$、$M_2$ and $M_3$ have already been translated of the z coordinates, they are also on the plane decided by $S_1$, $S_2$ and $S_3$. So put $M_1$ into formula (5), can obtain $z_{21}$ in the following formula:

$$\begin{aligned} z_{21}=z_{11}+ \\ &\frac{(x_{21}-x_{11})(y_{12}-y_{13})-(y_{21}-y_{11})(x_{12}-x_{13})}{C}z_{11}- \\ &\frac{(x_{21}-x_{11})(y_{12}-y_{13})-(y_{21}-y_{11})(x_{12}-x_{13})}{C}z_{12}+ \quad (6) \\ &\frac{(x_{21}-x_{11})(y_{11}-y_{12})-(y_{21}-y_{11})(x_{11}-x_{12})}{C}z_{13} \end{aligned}$$

For the two points $M_2$, $M_3$ , the process of working out $z_{22}$ and $z_{23}$ are consistent with the $M_1$ and $z_{21}$, just respectively replace the corresponding x and y values.

Thus, the mathematical model of magnetic suspended disk control system is established, we can see that there are two real target poles in this object, one is on the positive real axis and the other in the negative real axis, which is an instable second-order Hamilton system, only through closed-loop control can achieve stable work. At the same time we must consider the coupling among various channels, while calculating the control of one of loops, the other loops' influence to this loop should be considered.

## CONTROL SYSTEM DESIGN

Control system is the core link to achieve stable levitation of the magnetic suspended disk, thus while designing the system accuracy, real time accuracy and stability should be considered fully.

For formula (6) contains more multiplication and division, so the solving costs a longer time, occupancy control time, influence control effect, as if to improve control accuracy, the cost of control will increase. In order to obtain a certain control effect, without an increase in cost, displacement sensor and layout of the electromagnet can resolve this problem, that is the displacement sensors and the centre of the electromagnets distribute in the same circle (with radius R), and mutual spacing placed, each two are apart 60 degrees, the specific placement is shown in Figure 9.

According to Figure 9 can obtain the electromagnet and the displacement sensor's centre coordinates in the following:

$$\begin{aligned} & S_1(0, r, z_{11}), S_2\left(-\frac{\sqrt{3}}{2}r, -\frac{1}{2}r, z_{12}\right), \\ & S_3\left(\frac{\sqrt{3}}{2}r, -\frac{1}{2}r, z_{13}\right), M_1\left(-\frac{\sqrt{3}}{2}r, \frac{1}{2}r, z_{21}\right), \\ & M_2(0, -r, z_{22}), M_3\left(\frac{\sqrt{3}}{2}r, \frac{1}{2}r, z_{23}\right) \end{aligned} \tag{7}$$

Place formula (7) into formula (6) we can obtain:

$$\begin{cases} z_{21} = \dfrac{2z_{11} + 2z_{12} - z_{13}}{3} \\ z_{22} = \dfrac{-z_{11} + 2z_{12} + 2z_{13}}{3} \\ z_{23} = \dfrac{2z_{11} - z_{12} + 2z_{13}}{3} \end{cases} \tag{8}$$

Thus, by the craftiness arrangements of the structure, have simplified the mathematical model of the magnetic suspended disk, reduced hardware requirements and achieved a decoupling control of the magnetic suspended disk.

Thus, the entire control system's structure of disk is in Figure 10.

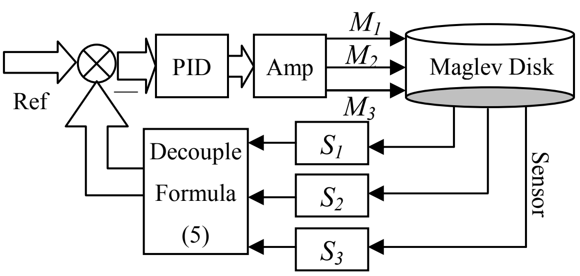


**FIGURE 10:** control system block diagram of magnetic suspended disk

PID control is a control method which is mature in technology widely used in the control theory. It owns the advantages of simple principle, easy to implement, robust and strong apply. In digital control system, PID control law is achieved by procedures, and therefore has greater flexibility [6].

Therefore use integral separation PID control algorithm, thus prevent the magnetic suspended disk from floating suddenly at the start, or output significant deviations at the end of the system, which will cause PID computing integral accumulation, cause a significant overshoot or even great scope oscillation. Integral separation is set an artificial domain of ε according to the actual situation; use the PD control while the error is big, use PID control while the error is small. The specified realization steps are in the following:

1) In accordance with the actual situation, set a threshold value $> 0$;

2) While |error（$k$）| > ε, use PD control;

3) While |error（$k$）| ≤ ε, use PID control, to ensure accuracy of the control system.

## ANALYSIS OF EXPERIMENT RESULT

Structure and electrical parameters of the magnetic suspended disk are as follows: disk mass of 1.2 Kg, magnetic area of $2.52\times10^{-4}m^2$, single-pole turns 2400, bias current of 2.5 A, offset position (gas gap) 12.5 mm. Amplifier adopt a half-bridge switching power amplifier, strong power-supply voltage of 120V DC. Displacement sensor using eddy current displacement sensor, Distinguish ratio of A/D and D/A converters of 12bit, D/A conversion rate of 60 μ s, A/D sampling period is 100 μ s, the control procedures is wrote with TC3.0 software, which runs in DOS environment, the control cycle is approximately 1 ms, the specific experimental prototype is shown in Figure 6.

Figure 11 and Figure 12 for the magnetic suspended disk's process from floating to stability and the corresponding control current curve. For recording the process, set up a control cycle in the procedures, output and record the value of displacement sensor and the corresponding control current, and then translate it into displacement which changes with time and the corresponding control current value, and using MATLAB software drawing the figures.

From Figure 11 and Figure 12 we can see, the system achieved stable suspension after 0.9 s, disk work interval [0,12.5 mm], obviously the overshoot is within the control scope, of this needs to elaborate particularly, the distance between the displacement sensors and the disc is 8 mm smaller than that of the electromagnet and the disk.

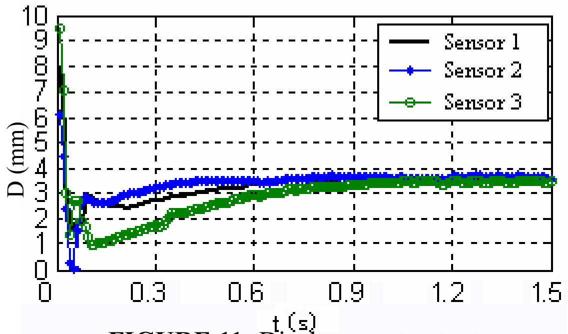

**FIGURE 11:** Displacement output

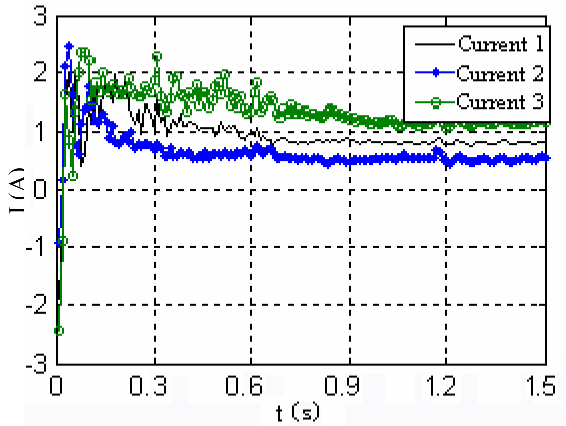

**FIGURE 12:** Control current

When disk suspends stably, respectively add horizontal and vertical direction interference, record the system's displacement and control current under the interference, using MATLAB software mapping, the actual proceeds disk displacement and the corresponding current are shown in Figure 13 and Figure 14.

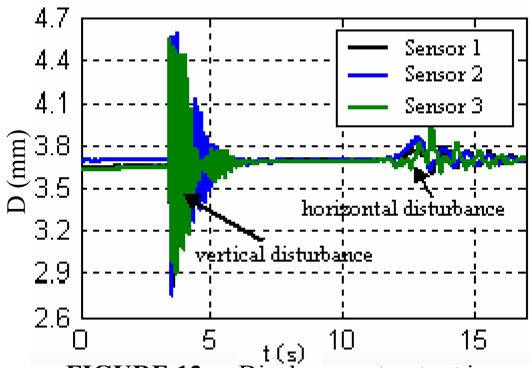

**FIGURE 13:** Displacement output in disturbance

It can be seen from Figure 13 and Figure 14, in the role of vertical interference, large oscillation appeared in the system, the amplitude large, but still within the scope of the work, it did not hit the assistive devices, and after the system's self-adjusting for a certain period of time, suspension achieved stability. And with the horizontal interference force, so long as not to surpass the electromagnet's effective work range, the system was stable.

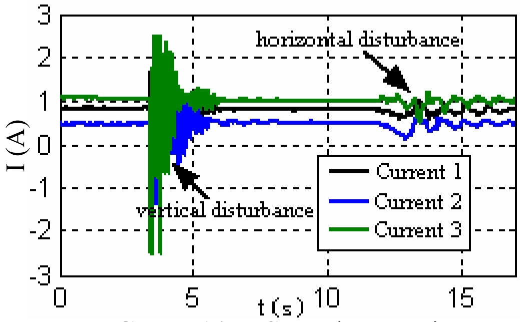

**FIGURE 14:** Control current in disturbance

Here, the horizontal interference is less than the vertical interference, besides, because while increasing the horizontal interference, component force exists in the vertical direction to a certain extent, resulting in system's oscillation in the vertical direction to a certain extent, the second half part of Figure 13 shows it.

## CONCLUSIONS

To sum up, firstly studied edge effect of the magnetic bearing, designed and developed a magnetic suspended device based on edge effect, introduced composition and work principle of magnetic suspended disk, established the mathematical model of the magnetic suspended disk control, and carried out the research on decoupling control, the hardware and software design, have done some work on control system modeling, decoupling control, and provide some reference value for the maglev technology applied to planar products and further studies.

Prototype experiment shows that the established model can accurately reflect the characteristics of control, and can achieve stable disk suspension; the adopted PID controller has good dynamic and static properties.

## ACKNOWLEDGEMENT

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