The Electromagnetic Analysis and Design of a New Permanent Magnetic Eddy Current Damper

XIE Hu, MA Shuyuan, LI Wenbin

Abstract—**The thesis suggests the design of a passive permanent magnetic eddy current damper. The damping force from the eddy currents which are generated by a conductor plate cutting through magnetic lines of forces can help make a maglev positioning platform more stable. The formulas for calculating damping force are proposed by applying molecular current methods. The feasibility of the design is proved by the finite element simulation of the proposed damper.**

Keywords—**Maglev Positioning Platform, Permanent Magnetic Eddy Current Damper, Molecular Current, Finite Element Analysis, Damping Coefficient**

I. INTRODUCTION

When a conductor moves in a magnetic field, it will be forced on Ampere's force by the induced current whose direction always hinders the movement of the conductor. This phenomenon is known as electromagnetic damping. Eddy current is generated by a moving conductor in a magnetic field, and it will be dissipated in the form of heat resistance. The main effects of an electromagnetic damper are braking and damping. As a new device and with the advantages of non-contact, mechanical friction free, lubrication free, controllable and measurable stiffness and damping properties, the electromagnetic damper has been paid growing attention since late 1970s[1].

Depending on different primary excitation sources, the electromagnetic damper has three sub-types: electrical excitation magnetic damper, hybrid excitation electromagnetic damper and permanent magnetic damper[2]. Electrical excitation magnetic damper can regulate the braking force by adjusting the air gap magnetic flux density amplitude. However, its braking force is lower in density and has more excitation magnetic loss. Hybrid excitation air gap magnetic field is under the effects of excitation winding and permanent magnets, with the advantages of large air gap magnetic amplitude, flexibility and high efficiency and the disadvantages of complicated structure and large size.

Permanent magnetic damper does not require extra power supply or excitation winding, so it is energy-saving, highly efficient and greater in braking density[3].

The design of a new permanent magnetic eddy current damper is proposed in this thesis, which can provide planar electromagnetic damping force on maglev positioning platform[4] and other accurate positioning systems and meet the needs of fast, accurate and stable positioning. Based on the structural design, the thesis suggests a three-dimensional simulation model of permanent magnetic eddy current damper by using finite element analysis software. The thesis also discusses how the air gap magnetic fields change in both stationary and working dampers and their different damping effects on maglev positioning platform.

II. THE STRUCTURE AND WORKING PRINCIPLE OF EDDY CURRENT DAMPER

The movement of a non-magnetic conductor in a magnetic field will lead to the cutting of magnetic lines and conductor. According to the law of electromagnetic induction, the cutting will generate electromotive in the conductor and then generate current. The distribution of the current varies because of the different conductor shapes and the varied magnetic flux. The path of the current looks like eddies in water, thus it is called electric eddy current. Eddy current has thermal effect and mechanical effect[5]. According to the principle of energy conservation, when an

Manuscript received December 08, 2013; revised January 13, 2014. This work was supported in part by the National Natural Science Foundation of China under Grant 51375052.

XIE Hu is a doctorate student from School of Mechanical Engineering, Beijing Institute of Technology, Beijing,100081, P. R. China (phone: 86-15010195742; e-mail: tmjamexh@163.com).

MA Shuyuan is a professor from School of Mechanical Engineering, Beijing Institute of Technology, Beijing,100081, P. R. China (e-mail: bitmc@bit.edu.cn).

LI Wenbin is a master-degree student from School of Mechanical Engineering, Beijing Institute of Technology, Beijing,100081, P. R. China (e-mail: liwenbinbit@163.com)

object is under the effect of eddy current damping (in other words damping force), the kinetic energy of the object transforms to thermal energy. The vibration of the object is thus reduced and the stable positioning of the object is achieved.

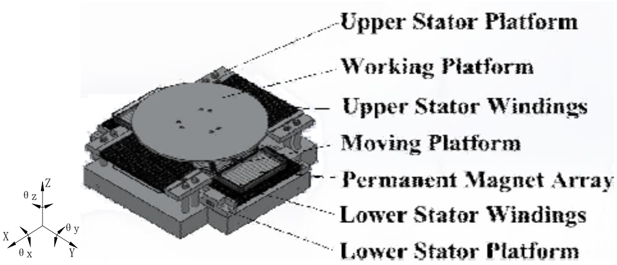
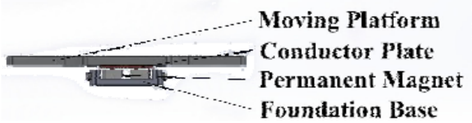
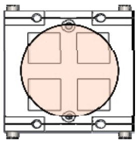


Fig. 1 The Overall Structure of the Maglev Positioning Platform



(a) The Front View



(b) The Top View

Fig. 2 Permanent Magnetic Eddy Current Damper

Figure 1 is the overall structure of the maglev positioning platform. The new design will meet the requirement of different nano-manufacturing experiments, greatly improving the experimental condition of the research on nano-manufacturing. The design can be used in the research of micro-nano mechatronics, the research and application of micro-nano devices’ assembly and measurement, and can serve as the platforms for fiber optic alignment, semiconductor testing and CMM as well. Figure 2 shows the permanent magnetic eddy current damper which is below the moving platform and without relative motion to the platform. The proposed damper in this thesis is a passive device, consisting of the magnetic source (a permanent magnet) and a conductor (a copper plate). Relative to the permanent magnetic array, the conductor plate moves horizontally at a certain speed; the magnetic field generated by the array changes as the plate moves through. The changing magnetic field will generate electromotive force in the plate and induce eddy current. According to Lenz’s law, the direction of the magnetic field generated by eddy current is opposite to the direction of the magnetic field generated by permanent magnet. The interaction between these two magnetic fields leads to a force that hinders relative movement—the electromagnetic damping force which suppresses the vibration of maglev positioning platform and helps make a more stable positioning. The proposed damper can also provide damping forces in two directions, simplifying the mechanical system of the damper and meeting the requirements of stability as well. The parameters of the proposed damper are shown in Table I.

Table I Parameters of Permanent Magnetic Eddy Current Damper

Parameter	Value
Radius of the Copper Plate(mm)	3.0
Thickness of the Copper Plate(mm)	5
Remanence of the Permanent Magnet(T)	1.35
Gap of Permanent Magnets(mm)	10
Width of the Permanent Magnet(mm)	20
Length of the Permanent Magnet(mm)	20
Thickness of the Permanent Magnet(mm)	10

III. THE MATHEMATIC MODEL OF PERMANENT MAGNETIC EDDY CURRENT DAMPER

A. The Magnetic Fields Distribution of Permanent Magnetic Eddy Current Damper

Based on the relative movement between maglev positioning platform and permanent magnetic eddy current damper, the relative movement between permanent magnet and non-magnetic copper conductor is shown in Figure 3. The permanent magnet used in the present study is rectangular with a square cross-section. Take its movement in Y direction for example, the conductor plate moves horizontally at the speed v above the magnet. From the magnet to observe in the direction of the plate, the eddy current distribution is as shown in Figure 4.

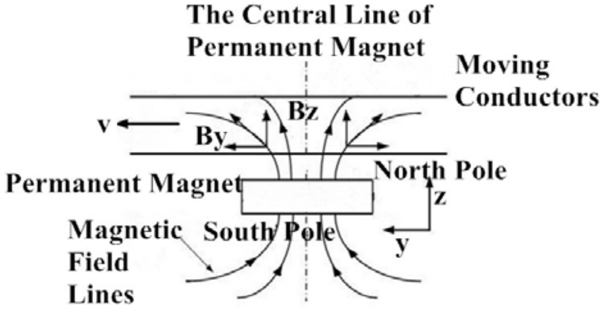


Fig. 3 The Relative Movement of Rectangular Permanent Magnet and Conductor

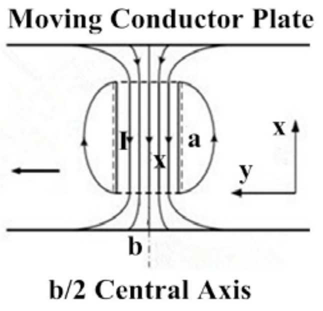


Fig. 4 The Distribution of Generated Current in the Conductor Plate

There are two magnetizing principles concerning magnetic medium, focusing on molecular current and magnetic charge respectively. The present study applies the method of molecular current to analyze the spatial three-dimensional magnetic field of the proposed damper. According to Ampere molecular circulation hypothesis, permanent magnet only has surface current but no volume current. Thus, the magnetic field of any external point outside the magnet can only be generated by the surface current circulation *ABCDA* as shown in Figure 5. The length and the width of the magnet are *a* and the thickness is *h*. The closed surface current element *dI* consists of the surface current circulation *A'B'C'D'A'* and $dI=J_1\cdot dz_0$. dz_0 is the height of the circulation *A'B'C'D'A'*.

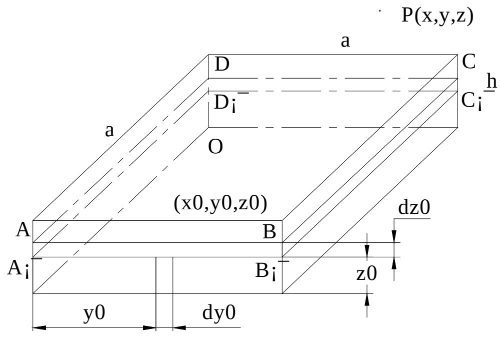


Fig. 5 The Distribution of Spatial Three-Dimensional Magnetic Field of the Rectangular Permanent Magnet

(x_0, y_0, z_0) is the position of a point on the surface of the permanent magnet; $P(x, y, z)$ is the position of a point outside the permanent magnet. The magnetic field intensity B caused by the effect of the permanent magnet on a certain point in the outer space is $B=B_X\,\mathbf{i}+B_Y\,\mathbf{j}+B_Z\,\mathbf{k}$. B_X, B_Y and B_Z are components of B along X, Y and Z. According to the right-hand rule, the damping force has no relation to the components B_X and B_Y which are along the directions of X and Y in spatial magnetic field, but it is related to B_Z along the vertical direction. The current loop *A'B'C'D'A'* is made up of four currents. It is assumed that the spatial three-dimensional magnetic field intensity generated by each current is dB_1, dB_2, dB_3, dB_4. B_Z, the component along Z direction in the spatial magnetic field around the permanent magnet, is as follows,

$$B_Z=\int_0^h (dB_{z1}+dB_{z2}+dB_{z3}+dB_{z4})\vec{k} \qquad (1)$$

According to Biot-Savart law, the vertical magnetic field generated by the remanent three currents of *A'B'C'D'A'* loop is

$$\begin{cases} dB_{z1}=\dfrac{\mu_0 J_1 dz_0}{4\pi}\displaystyle\int_0^b \frac{a-x}{\left[(x-a)^2+(y-y_0)^2+(z-z_0)^2\right]^{\frac{3}{2}}}dy_0 \\ dB_{z2}=\dfrac{\mu_0 J_1 dz_0}{4\pi}\displaystyle\int_0^a \frac{b-y}{\left[(x-x_0)^2+(y-b)^2+(z-z_0)^2\right]^{\frac{3}{2}}}dx_0 \\ dB_{z3}=\dfrac{\mu_0 J_1 dz_0}{4\pi}\displaystyle\int_0^b \frac{x}{\left[x^2+(y-y_0)^2+(z-z_0)^2\right]^{\frac{3}{2}}}dy_0 \\ dB_{z4}=\dfrac{\mu_0 J_1 dz_0}{4\pi}\displaystyle\int_0^a \frac{y}{\left[(x-x_0)^2+y^2+(z-z_0)^2\right]^{\frac{3}{2}}}dx_0 \end{cases} \qquad (2)$$

$\mu_0=4\pi\times 10^{-7}$is the permeability in the vacuum.

Using the above formula and integral in the thickness direction of the permanent magnet, the component B_Z along Z direction is

$$B_z=K\left(\int_0^h\left(\begin{array}{l}\displaystyle\int_0^b \frac{a-x}{\left[(x-a)^2+(y-y_0)^2+(z-z_0)^2\right]^{\frac{3}{2}}}dy_0 \\ \displaystyle+\int_0^a \frac{b-y}{\left[(x-x_0)^2+(y-b)^2+(z-z_0)^2\right]^{\frac{3}{2}}}dx_0 \\ \displaystyle+\int_0^b \frac{x}{\left[x^2+(y-y_0)^2+(z-z_0)^2\right]^{\frac{3}{2}}}dy_0 \\ \displaystyle+\int_0^a \frac{y}{\left[(x-x_0)^2+y^2+(z-z_0)^2\right]^{\frac{3}{2}}}dx_0\end{array}\right)dz\right) \qquad (3)$$

Assume $K=\mu_0 J_1/4\pi=\mu_0 M/4\pi=Br/4\pi$, K is a constant, Br is the remanence of the permanent magnet, using Tesla as its unit.

B. The Damping Force of Permanent Magnetic Eddy Current Damper

The induced electromotive force in the moving conductor plate is $E=v\times B_Z$. From the value of e.m.f. E, the induced current density J of a particular point within the projection area of the conductor plate on the permanent magnet is $J=\sigma E=\sigma v B_Z$, and σ is the electrical resistivity of the conductor, E is the induced electromotive force. According to Ampere's law, the interaction between J (the induced current density) and BZ (the vertical component in the magnetic field of the permanent magnet) is affected by eddy current force F which is in the opposite direction to the moving direction of the conductor.

$$F = \iiint df = \iiint J \times B_z dV$$
$$= \iiint_{\Sigma_1} \sigma_1 \mathrm{v} \mathrm{B}_z^{\,2} d\mathrm{V} + \iiint_{\Sigma_2} \sigma_2 \mathrm{v} \mathrm{B}_z^{\,2} d\mathrm{V} \quad (4)$$

σ_1 is the electrical resistivity of the copper plate conductor; σ_2 is the electrical resistivity of the materials used in the maglev platform; Σ_1 is the domain of integration of the copper plate and Σ_2 is the domain of integration of the maglev platform.

C. The Damping Parameters of Permanent Magnetic Eddy Current Damper

According to the definition of damping parameters, *D* (the damping parameter of the eddy current damper) is the ration between *F* (the damping force on the conductor plate) and *v* (velocity). Thus,

$$\mathrm{D} = \frac{F}{v} = \iiint_{\Sigma_1} \sigma_1 \mathrm{B}_z^{\,2} dv + \iiint_{\Sigma_2} \sigma_2 \mathrm{B}_z^{\,2} d\mathrm{V} \quad (5)$$

IV. THE SIMULATION ANALYSIS OF PERMANENT MAGNETIC EDDY CURRENT DAMPER

A. The Magnetic Simulation of the Permanent Magnets Array

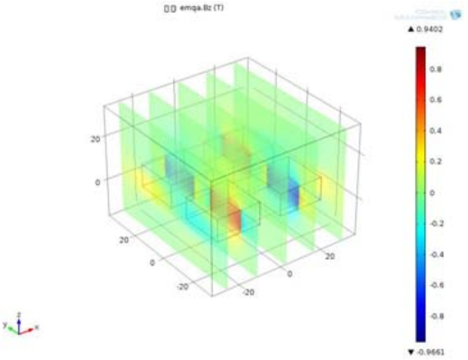
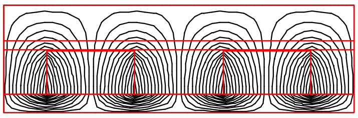


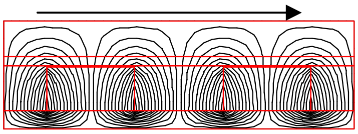
Fig. 6 The Magnetic Flux Density of Permanent Magnets Array

The directions of the horizontal movements of the maglev positioning platform are *X* and *Y*. Because the motion platform and the permanent magnetic eddy current damper of the maglev positioning platform are symmetrically located in the directions of *X* and *Y*, there will be equivalent damping force and damping parameters when the maglev positioning platform is moving along *X* and *Y* directions. Meanwhile, the design is simple in mechanical structure. A three-dimensional finite element model of the magnetic source is built to analyze the distribution of air gap magnetic field of the proposed damper. Figure 6 is the finite element simulation of the air gap magnetic field.

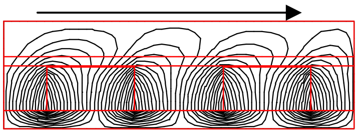
B. The Simulation of the Magnetic Field of Permanent Magnetic Eddy Current Damper



(a) V(Conductor Plate)=0



(b) V(Conductor Plate)=0.1 m/s



(c) V(Conductor Plate)=5 m/s

Fig.7 The Magnetic Lines Distributions of Permanent Magnetic Eddy Current Damper

Figure 7 shows the finite element simulation of damping forces in different velocity, applying the damper's parameters listed in Table 1. As shown in the figure, when the relative velocity between the conductor and the magnetic source increases, there will be an increase in the damping force as the inclination angles of magnetic lines become bigger. The damping force increases because the magnetic field of the permanent magnet is affected by the magnetic field of the eddy current. The bigger the induced current in the conductor plate, the greater its effect on the permanent magnet.

V. CONCLUSION

The thesis suggests the design of a passive permanent magnetic eddy current damper that can be used in a maglev positioning platform. Based on molecular current methods, the research derives the formulas of air gap magnetic field and of calculating the damping parameters and the damping forces. The feasibility of the design is proved by the magnetic finite element simulation of the proposed damper.

REFERENCE

[1] WANG Haihang, WANG Xixuan. "Effect of Control Algorithms on Dynamic Characteristics of Active Magnetic Damper". *Journal of Vibration Engineering*, vol. 4, pp. 330-335, Jul. 1994. 汪海航，汪希

萱。控制算法对电磁阻尼器动力特性的影响[J] 振动工程学报，1994,7(4)：330-335.

[2] ZHANG He, KOU Baoquan, JIN Yinxi, YANG Guolong, ZHAO Xionghao. “Characteristics Analysis of Planar Electromagnetic Dampers”. *Proceedings of the CSEE*, vol. 33(21), pp. 138-144, 2013. 张赫，寇宝泉，金银锡，杨国龙，赵雄浩。平面电磁阻尼器的特性分析[J] 中国电机工程学报，2013,33(21）：138-144.

[3] KOU Baoquan, JIN Yinxi, ZHANG He, ZHANG Hailin, YANG Jun. “Characteristics Analysis of Hybrid Excitation Linear Electromagnetic Damper”. *Proceedings of the CSEE*, vol. 33(24), pp. 143-151, 2013. 寇宝泉，金银锡，张赫，张海林，杨俊。混合励磁直线电磁阻尼器的特性分析[J] 中国电机工程学报，2013，33(24)：143-151.

[4] MA Shuyuan, XIE Hu, WANG Weiming, SHAN Mingcai, SONG Qian. Maglev Positioning Platform [P] 201210494634.8 2012-12-20. 马树元，谢虎，王伟明，闪明才，宋谦。磁悬浮式定位平台[P] 201210494634.8 2012-12-20.

[5] TANG Yusheng. “Working Principle of Eddy Current Retarder and Its Common Problems and Maintenance”. *Auto Electric Parts*, pp. 48-50, Oct. 2008. 汤玉胜.电涡流缓速器工作原理及常见问题与维护[J] 汽车电器,2008.10:P48-50.