The Analysis of Electromagnetic Relay's Dynamic Characteristics Disturbed by Uniform Constant Magnetic Field

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***Abstract* — This paper computed the dynamic characteristics of a clap-type electromagnetic relay by the software FLUX3D*, considering the disturbance of uniform magnetic field outside the relay. The effects of external magnetic field on dynamic parameters and the condition that the relay cannot operate abnormally were analyzed. This method proposed by this paper can be used to evaluate the electromagnetic relay's electromagnetic compatibility (EMC) in the environment full of static magnetic field.**

***Index Terms*—dynamic characteristics, uniform constant magnetic field, electromagnetic relay, FLUX3D, EMC**

I. INTRODUCTION

Electromagnetic relay is widely used in the area of aerospace, communication and industry automation. With the development of design thinking, the control system using relays becomes more and more integral and intelligent, so that many control devices (such as electromagnetic relay, solid-state relay, semiconductor power devices and etc) are installed in a small space, where the magnetic field generated from one device may greatly affect on another device's normal function. In order to obtain accurately the effect on the function of electromagnetic relay and evaluate the relay's EMC, it is necessary to analyze the relay's dynamic characteristics taking account into uniform external magnetic field.

Recently, some studies on the dynamic characteristics of twin-type electromagnetic relay in a small space and the interference between them have been made [1]. The effect on electromagnet's dynamic characteristics by exerting different voltages and different duty factors on the coil also was investigated [2]-[4]. The literature [5] analyzed the effects of external disturbing magnetic field on electromagnetic relay's static characteristics. However, little work is done on the effect of relay's dynamic characteristics disturbed by external magnetic field.

In this paper, a clap-type relay's pick-up process disturbed by different external magnetic flux densities were calculated using the software FLUX3D. The coil's exciting current and armature's angle displacement computed agree with experimental results, when there is no external magnetic field disturbing. Then, this paper gave the time variations of dynamic parameters and the external magnetic field variations of dynamic parameters. Furthermore, we analyzed the condition that the relay cannot operate correctly, when the value of disturbing magnetic field is large enough.

II. THEORETICAL BACKGROUND AND FORMULATIONS

The formulations implemented for this paper's problem in FLUX3D can be written as follows:

$$\mathrm{div}([\mu_\mathrm{r}]\mu_0(-\mathrm{grad}(\phi_\mathrm{tot}))+\boldsymbol{B}_\mathrm{r})=0 \tag{1}$$

$$\mathrm{rot}\phi_\mathrm{tot}=0 \tag{2}$$

$$\mathrm{div}([\mu_\mathrm{r}]\mu_0(-\mathrm{grad}(\phi_{\mathrm{redT_o}})+\boldsymbol{T}_\mathrm{o})+\boldsymbol{B}_\mathrm{r})=0 \tag{3}$$

$$\mathrm{rot}\phi_{\mathrm{redT_o}}=0 \tag{4}$$

$$\mathrm{rot}\boldsymbol{T}_\mathrm{o}=\boldsymbol{J}+\mathrm{rot}\boldsymbol{H}_\mathrm{jw} \tag{5}$$

where [μ_r] is the tensor of relative magnetic permeability of the medium, μ_0 is the magnetic permeability of the vacuum, ϕ_tot is the total magnetic scalar potential, $\boldsymbol{B_r}$ is the remanent magnetic flux, $\boldsymbol{T_o}$ is the electric vector potential, and ϕ_totTo is the reduced magnetic scalar potential with respect to $\boldsymbol{T_o}$, $\boldsymbol{J}$ is the current density, $\boldsymbol{H_{jw}}$ is the approximation with edge elements of the field $\boldsymbol{H_j}$ due to non-meshed conductors and computed by Biot and Savart.

For this paper problem, the equations (1) and (2) are used for the magnetic regions, and the equations (3), (4) and (5) are used for the air and non-meshed coil regions.

When the voltage source is applied to the coil of relay, the magnetic field can be calculated coupling in the equations (3), (4), (5) and the electric circuit equation as follows:

$$V_0=RI_0(t)+\frac{d\psi(t)}{dt} \tag{6}$$

where V_0 is the applied voltage, R is the resistance, I_0 is the exciting current, and Ψ is the interlinkage flux of the coil.

When the torques acts on armature, the armature rotates. The rotary motion equation is

$$I\frac{d^2\theta}{dt^2}+T_\mathrm{r}=T_\mathrm{m} \tag{7}$$

where T_m is the electromagnetic torque acting on the armature, I is the moment of inertia of the armature, θ is the rotation angle of the armature, and T_r is the torque by reeds.

III. MODEL OF SIMULATION

In this paper, the research object is a clap-type relay. It comprises stator, armature, coil and reeds. The coil's voltage is 24V, and its resistance is 1090Ω. Because of symmetry, only half of the model was built. Fig.1 shows the solid model of its electromagnetic system. Fig.2 indicates the curve of reeds' torque. The armature's drop-out position and pick-up position are corresponding to the zero degree and 3.2 degrees respectively.

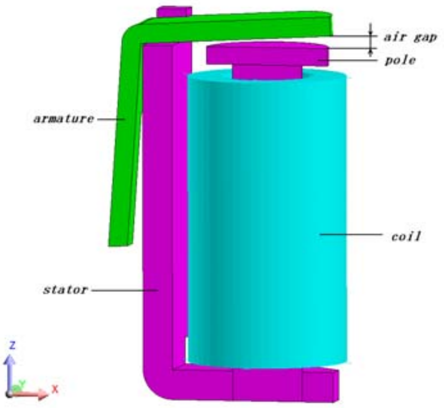

Fig.1. Model of the clap-type relay by FLXU3D.

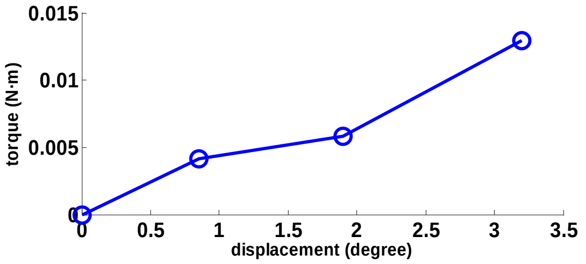

Fig.2. Torque by reeds

In order to generate uniform magnetic field, a long current coil is put outside the relay and it contains the relay completely. Fig.3 is the top view of the whole model. The relay is in the centre of the coil.

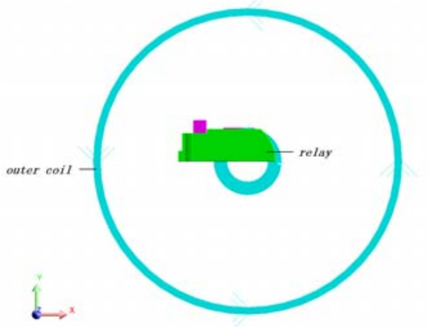

Fig. 3. Top view of the whole model

When the length of the coil is infinite, the magnetic flux density inside the coil is uniform and its value is calculated by the following equation:

$$B = \mu_0 NI \qquad (8)$$

where N is the turns' number per meter, I is the current of the coil.

In this paper, the coil length l_{coil} is 0.15m, which is nearly 7.5 times as long as the relay longest side's. The turns' number of the coil is 119366, and coil current is 1A. According to equation (8), the magnetic flux density inside the coil is 1T. Fig.4 indicates the magnetic flux density's result calculated by FLUX3D, which is about 0.966T and quite uniform in space of the relay. Hereby, we use the coil outside the relay to simulate the external uniform magnetic field.

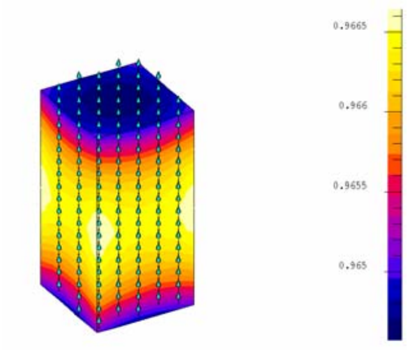

Fig.4. Magnetic flux density generated by the coil

IV. RESULTS AND DISCUSSION

A. *Sensitive Direction*

Different disturbing magnetic field directions have different effects on the dynamic characteristics of the relay. But among of all the directions in space, there is a most sensitive direction at the drop-out position. That is, in this direction, the disturbing magnetic field has bigger influence on the relay than other directions with the same value. In order to evaluate the relay's capability of enduring disturbing magnetic field, it is necessary to find the most sensitive direction first. This paper finds the sensitive direction by calculating the torque of the armature in different directions in space. This method is presented in the literature [5]. The result shows that the most sensitive direction has about 30 degrees with the axis of the iron core and inclines to sub yoke in the x-z plane of the global Cartesian coordinate system. It is showed in Fig.5. If the external magnetic field makes the air gap's field increase in this direction, the armature's electromagnetic torque will be the largest one among all directions in space with the same magnetic field value. And if it reduces the air gap's field, the electromagnetic torque will be the smallest one. This paper uses the negative value of magnetic flux density as the value of external magnetic flux density which makes the air gap's field reduce. And positive values are used for values of the magnetic field whose direction is opposite.

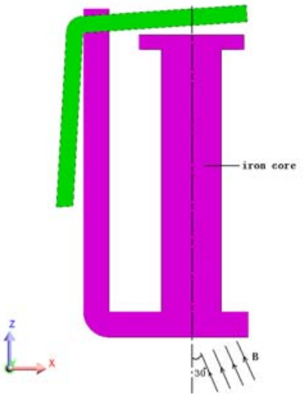

Fig.5. The most sensitive direction

B. *Dynamic Characteristics with Different External Magnetic Fields*

Fig.6 shows calculated result of coil's current and measured result without disturbing by external magnetic field. The current was measured by oscillograph. In Fig7, the armature's angle displacement (result measured) was taken by test system with Charge Coupled Device (CCD).

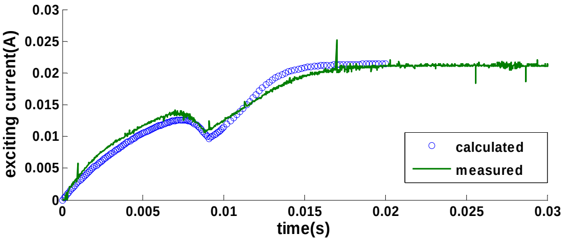

Fig.6. Time variations of exciting current

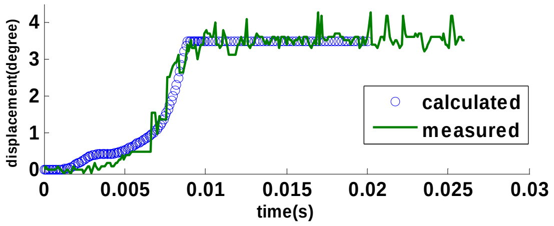

Fig.7. Time variations of armature's displacement

Fig.8-11 show time variations of exciting current, angle displacement, electromagnetic torque and angle velocity respectively in environments with different external magnetic field strengths. In the Fig.8, it shows that exciting current during pick-up time is different with different external magnetic field disturbing. The external magnetic field reducing air gap's magnetic field makes the exciting current increase, and the external magnetic field increasing air gap's magnetic field brings it down. From Fig.9-10, it can see that the external magnetic field reducing air gap's magnetic field makes the pick-up time much longer, greatly reduces the electromagnetic torque. Fig.11 shows that the armature's angle velocity decreases greatly, and the armature even reverses its rotation direction near the pick-up position, when the external magnet field is -0.015T.

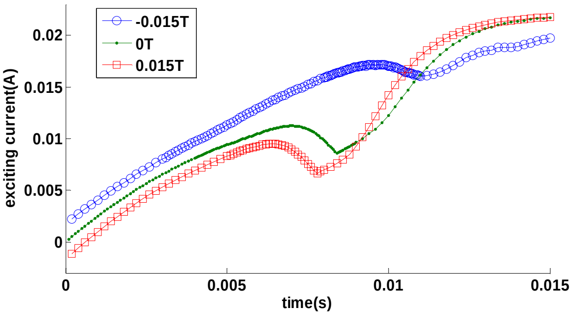

Fig.8. Time variations of exciting current

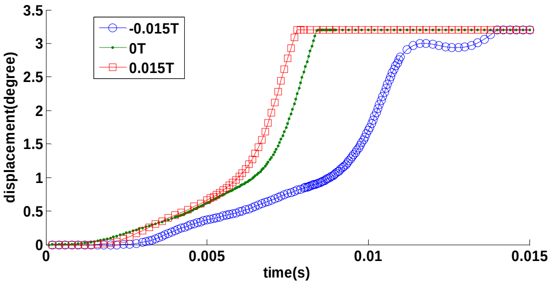

Fig.9. Time variations of angle displacement

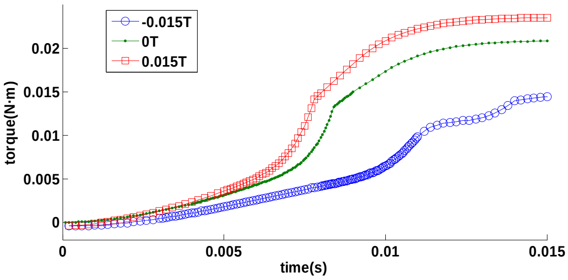

Fig.10. Time variations of electromagnetic torque

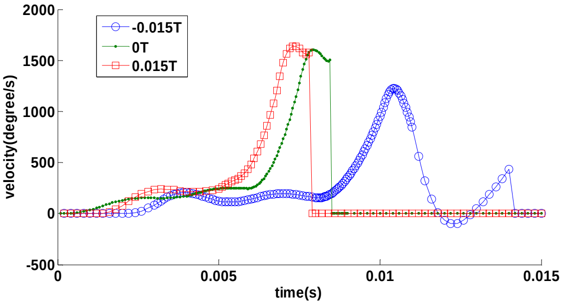

Fig.11. Time variations of angle velocity

C. *Relation between Dynamic Parameters and External Magnetic Field*

From Fig.12, it is found that external magnetic field delays the armature's motion, no matter it is to increase or reduce the magnetic field by the relay's coil. Furthermore, the time increases nearly linearly along with the external magnetic flux density increasing, and the external magnetic field reducing the magnetic field of the air gap makes it increase faster.

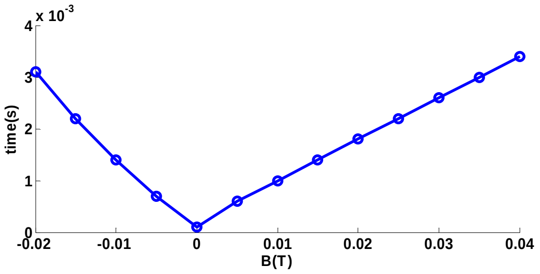

Fig.12. External magnetic flux density variations of time beginning to move

Fig.13 shows that pick-up time increases faster with external magnetic field increasing, which reduces the magnetic field of the air gap, and with the increasing of external magnetic field which increases the magnetic field of the air gap, the pick-up time changes little, and is nearly the same.

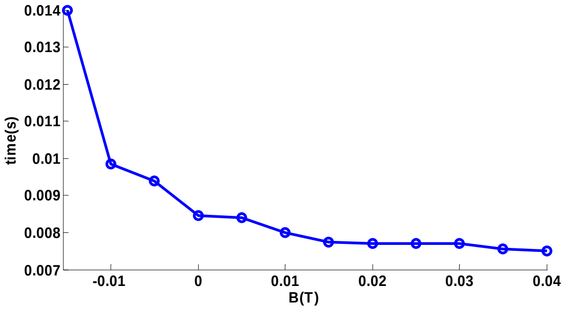

Fig.13. External magnetic flux density variations of pick-up time

From Fig.14, it is found that external magnetic which reduces the air gap's magnetic field makes the attractive force between armature and pole decrease greatly at the pick-up position. Although external magnetic field increasing the air gap's magnetic field makes the final force increase, because of the magnetic circuit's saturation, the torque grows more and more slowly with external magnetic field increasing. Fig.15 shows the angle velocity at the pick-up position.

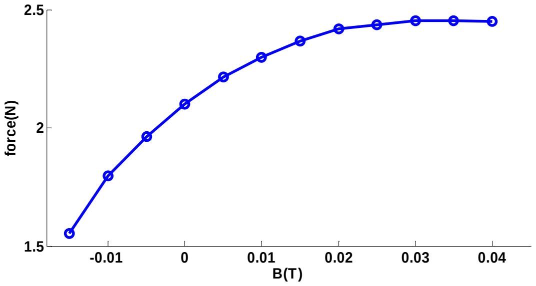

Fig.14. External magnetic flux density variations of attractive force between armature and pole at the pick-up position

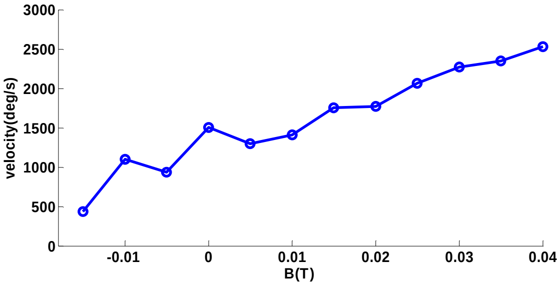

Fig.15. External magnetic flux density variations of angle velocity at the pick-up position

D. *Incorrectly Operating Analysis*

Fig.16-19 shows the time variations of exciting current, torque by magnetic field, torque by reeds, angle displacement and angle velocity, when the value of external magnetic flux density is -0.02T. After 0.025s, the exciting current reached its stable value. The electromagnetic torque and the torque by reeds were nearly equal, and the angle velocity of the armature was approximately zero degree per second. But the angle displacement of the armature was only 2.285 degrees, and did not reach the pick-up position. It means that the relay could not operate correctly under this condition; the armature finally stopped at the position between drop-out position and pick-up position.

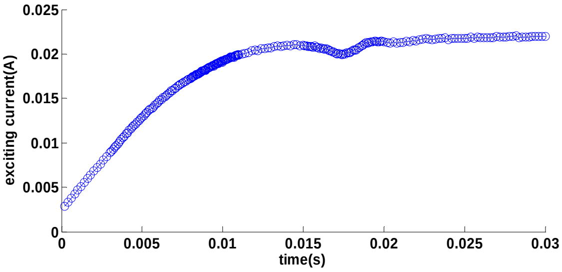

Fig.16. Time variations of exciting current

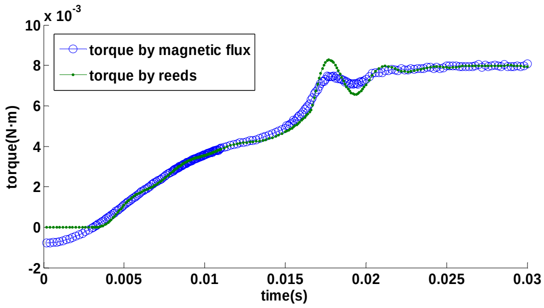

Fig.17. Time variations of torque by magnetic field and torque by reeds

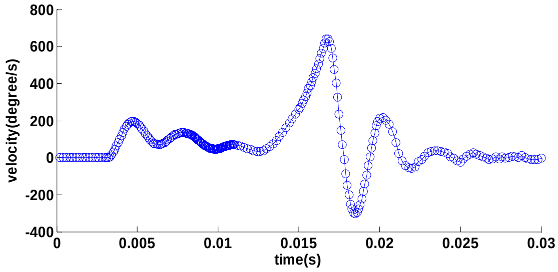

Fig.18. Time variations of angle velocity of the armature

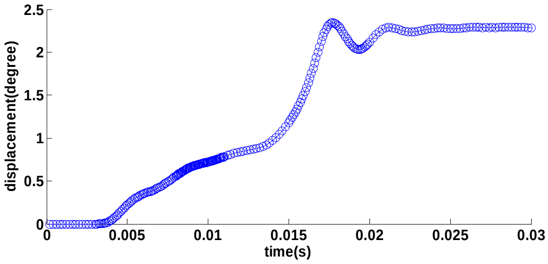

Fig.19. Time variations of angle displacement of the armature

V. CONCLUSION

In this paper, we computed the clap-type relay's dynamic characteristics by FLUX3D in the environment which is full of uniform magnetic field. It is found that the external magnetic field delays the armature's motion, no matter it is to reduce or increase the air gap's magnetic field. The external magnetic field reducing the air gap's magnetic field by the relay's coil has greater effect on dynamic parameters (such as time beginning to move, pick-up time, final force between armature and pole, and final angle velocity) than magnetic field whose direction is opposite. It makes time beginning to move and pick-up time become longer, and decreases the torque acting on the armature and angle velocity at the pick-up position. When the value of the external magnetic field is -0.02T, the armature cannot operate correctly. The method proposed in this paper can be used to evaluate the electromagnetic relay's capability of enduring static magnetic field's disturbance.

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* Web side of FLUX software: www.cedrat.com.