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Research on electromagnetic relay's dynamic characteristics disturbed by uniform static magnetic field*

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Abstract: Electromagnetic relay is a widely used apparatus which usually works in a magnetic disturbance environment. To evaluate its electromagnetic compatibility (EMC) in a static magnetic field, dynamic characteristics of a clapper relay in a uniform static magnetic field situation based on the finite element method (FEM) is studied. Influences of the magnetic field on dynamic parameters (delay time, pick-up time, end pressure, and final velocity) as well as a situation in which the relay cannot function normally are analyzed. Simulation reveals that the external magnetic field which weakens the relay's air-gap field has a greater influence on the relay's dynamic parameters than the one strengthening the field. The validity of the simulation is verified by measured results of coil current and armature displacement.

Key words: Dynamic characteristics, Uniform static magnetic field, Electromagnetic relay, Finite element method (FEM), Electromagnetic compatibility (EMC)

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INTRODUCTION

An electromagnetic relay is a widely used apparatus in the fields of aerospace, communication, industrial automation, etc. With the increasing integration of control systems, many devices (such as electromagnetic relay, solid-state relay, power semiconductor, etc.) are installed in a small space, where the magnetic field generated by one device may greatly affect another (Shigeki, 1989; Hosaka and Kuwano, 1994; Nils and Dieter, 1999). In order to accurately obtain influences of the static magnetic disturbance on an electromagnetic relay and evaluate its electromagnetic compatibility (EMC), it is necessary to analyze the relay's dynamic characteristics in a uniform static magnetic field situation.

Dynamic characteristics of a twin-type electromagnetic relay in a small space and the interference between them were studied (Yamaguchi *et al*., 2002). The effects on the electromagnetic relay's dynamic characteristics by applying different voltages and different duty factors on the coil were investigated (Kawase *et al*., 1994; Mitsutake *et al*., 1997; Kawase *et al*., 2006). And the effects of a disturbing magnetic field on the electromagnetic relay's static characteristics (Zhou *et al*., 2006; Yang *et al*., 2007) were also researched. However, little work has been done on the effects of the relay's dynamic characteristics disturbed by a magnetic field.

In this paper, a clapper relay's pick-up process disturbed by different magnetic fields is calculated based on the finite element method (FEM). The computed coil's exciting current and armature's displacement agree well with the experimental results without disturbance of the magnetic field. Then, curves of dynamic parameters versus time as well as curves of dynamic parameters versus magnetic flux density magnitude are given. Finally, we analyze the condition in which the relay cannot operate correctly in a 0.02 T disturbing magnetic field.

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THEORETICAL BACKGROUND AND FORMULATIONS

The magnetic field of relay is solved by the magnetic scalar potential method. Fundamental formulations are shown as follows:

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

$$\mathrm{rot}\,\Phi_\mathrm{tot}=0, \tag{2}$$

$$\mathrm{div}\left([\mu_\mathrm{r}]\mu_0(-\mathrm{grad}(\Phi_{\mathrm{red}\boldsymbol{T}_\mathrm{elec}})+\boldsymbol{T}_\mathrm{elec})+\boldsymbol{B}_\mathrm{r}\right)=0, \tag{3}$$

$$\mathrm{rot}\,\Phi_{\mathrm{red}\boldsymbol{T}_\mathrm{elec}}=0, \tag{4}$$

$$\mathrm{rot}\boldsymbol{T}_\mathrm{elec}=\boldsymbol{J}+\mathrm{rot}\boldsymbol{H}_{\boldsymbol{J}\mathrm{Approx}}, \tag{5}$$

where $[\mu_\mathrm{r}]$ is the tensor of relative permeability of the medium, μ_0 is the permeability of the vacuum, Φ_tot is the total magnetic scalar potential, $\boldsymbol{B}_\mathrm{r}$ is the remanent flux density, $\boldsymbol{T}_\mathrm{elec}$ is the electric vector potential, $\phi_{\mathrm{red}\boldsymbol{T}_\mathrm{elec}}$ is the reduced magnetic scalar potential with respect to $\boldsymbol{T}_\mathrm{elec}$, $\boldsymbol{J}$ is the current density, and $\boldsymbol{H}_{\boldsymbol{J}\mathrm{Approx}}$ is the approximation with edge elements of the field $\boldsymbol{H}_{\boldsymbol{J}}$ due to non-meshed conductors and computed by the Biot-Savart law.

Eqs.(1) and (2) which solve the total magnetic scalar potential are used for ferromagnetic regions. Eqs.(3)~(5), which solve the reduced magnetic scalar potential, are used for the air and non-meshed coil regions coupled with an external circuit.

When the voltage source is applied to the relay's coil, the magnetic field of the coil can be calculated by coupling the electric circuit Eq.(6):

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

where V_0 is the voltage applied on the relay's coil, R is the resistance, I_0 is the exciting current, and ψ is the flux linkage of the coil.

Attractive torque and reaction torque make the armature rotate, which can be described as:

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

where T_m is the attractive torque applying to the armature, I is the moment of inertia of the armature, θ is the rotation angle, and T_r is the torque produced by reeds.

MODEL OF SIMULATION

The clapper relay consists of a yoke iron, an iron core, a pole shoe, an armature, a coil and three reeds. Its coil voltage is 24 V, and the coil resistance is 1090 Ω. Because of symmetry, only half of the model is built. Fig.1 shows the solid model of its electromagnetic system. Fig.2 indicates the characteristic curve of the reaction torque. Positions of drop-out and pick-up are 0° and 3.2°, respectively. B-H curve of ferromagnetic material is shown in Fig.3.

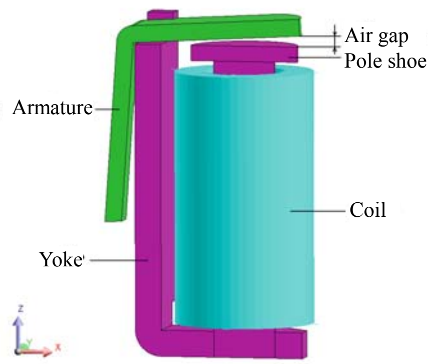

Fig.1 Model of the clapper relay built by FLXU3D

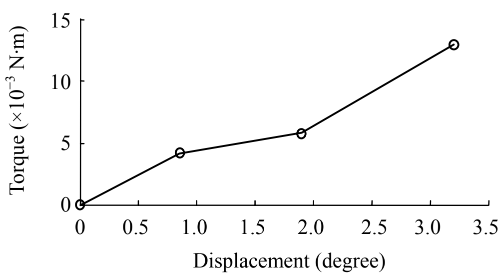

Fig.2 Characteristic curve of the reaction torque

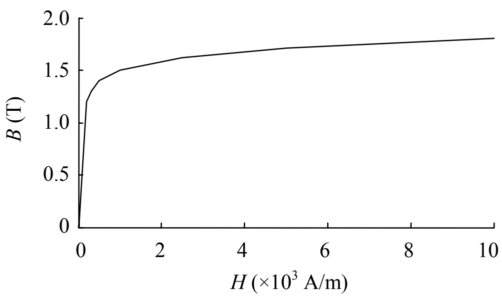

Fig.3 *B-H* curve of the ferromagnetic material

Combining Ampere's law with Gauss's law for magnetism, a uniform magnetic field can be obtained in a long solenoid, and the magnitude of $\boldsymbol{B}$ is expressed as:

$$B = \mu_0 N I_{solenoid}, \qquad (8)$$

where N is the coil's turn number per meter, $I_{solenoid}$ is the current of the solenoid.

In this paper, the relay is placed in the centre of a uniform static magnetic field produced by a long solenoid, whose top view is shown in Fig.4.

The solenoid's length $l_{solenoid}$ is 0.15 m, which is almost 7.5 times as long as the relay's longest side. Its turn number is 119366. According to Eq.(8), the internal $\boldsymbol{B}$ of the solenoid is 1 T when its current is 1 A. Fig.5 shows the distribution of $\boldsymbol{B}$, which indicates that the internal magnetic field is quite uniform with a magnitude of almost 1 T. Hereby, the solenoid can be served as the disturbing uniform magnetic field.

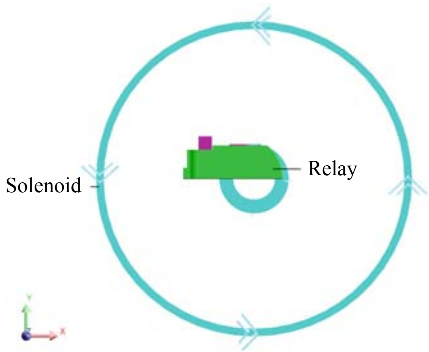

Fig.4 Top view of the analyzed model

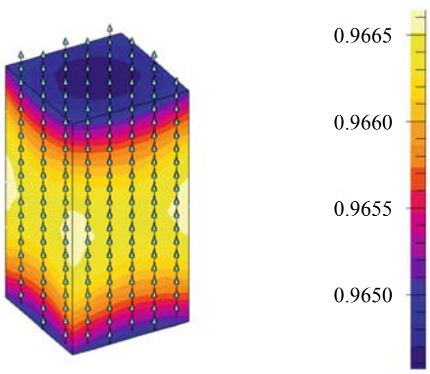

Fig.5 Distribution of *B* generated by solenoid

RESULTS AND DISCUSSION

Sensitive direction

In each position of the armature, different disturbing magnetic field directions have different effects on the dynamic characteristics of the relay, but there is only one direction that influences it most significantly, which is called the sensitive position. In order to evaluate the relay's endurance of magnetic field disturbance, it is necessary to find its sensitive direction first. As the variation of the armature's position is quite small, to simplify the analysis we regard the sensitive direction when the armature is in the drop-out position as the sensitive direction of the relay.

The sensitive direction of the drop-out position is shown in Fig.6, which is found by calculating the armature's attractive torque in a uniform static magnetic field with different directions (Zhou *et al*., 2006). In this direction, when the disturbing magnetic field strengthens the air-gap field, the attractive torque will be the maximum. When the magnetic field weakens the air-gap field, the torque will be the minimum, and the magnitude of disturbing flux density is assumed to be negative.

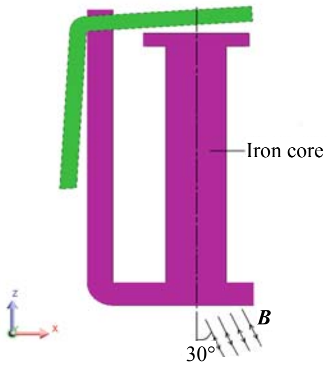

Fig.6 Sensitive direction of the relay

Dynamic characteristics disturbed by magnetic field in sensitive direction

Calculated and measured results of exciting current without magnetic disturbance are shown in Fig.7a, and the current is measured by an oscilloscope. Calculated and measured results of the armature's displacement without magnetic disturbance are shown in Fig.7b, and the displacement is measured by a charge coupled device (CCD) testing system (Yin *et al*., 2005). The calculated results in Fig.7 agree well with the experiments.

Dynamic characteristics of the relay disturbed by a 0.015 T and −0.015 T uniform magnetic field are calculated, respectively, which are shown in Fig.8.

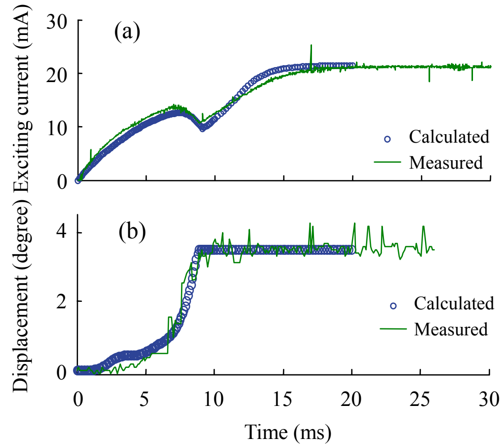

Fig.7 Calculated and measured results of the exciting current (a) and the armature's displacement (b)

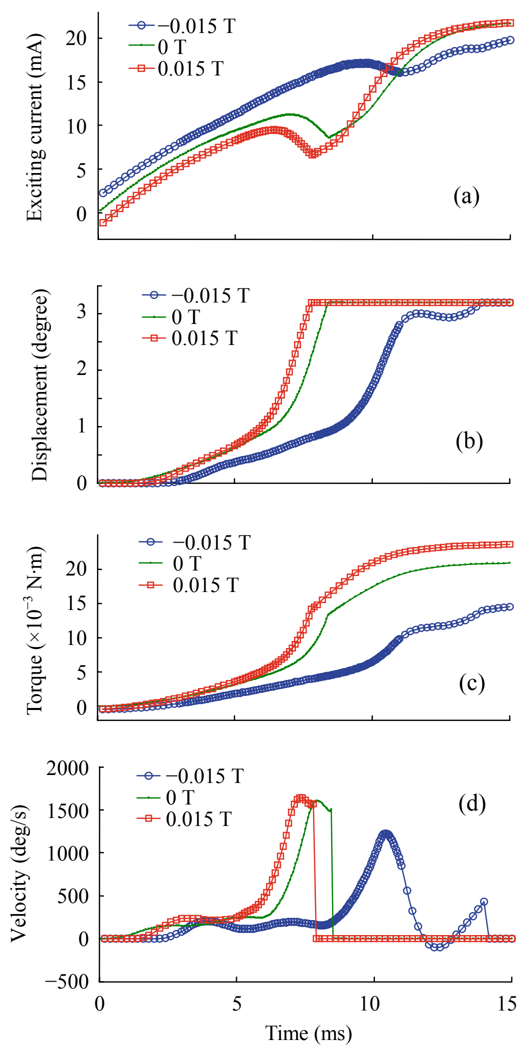

Fig.8 Exciting current (a), displacement (b), attractive torque (c), and velocity (d) disturbed by different magnetic fields

Fig.8a shows that exciting currents are different when disturbed by different magnetic fields during the pick-up process. The −0.015 T disturbing field increases the exciting current, while the 0.015 T field decreases it. Fig.8 indicates that the −0.015 T disturbing field has a larger influence on the relay's dynamic characteristics including exciting current, displacement, attractive torque and velocity. Fig.8d shows that when the disturbing field is −0.015 T, the armature's velocity decreases greatly, and its direction even reverses near the pick-up position.

Relationships between dynamic parameters and disturbing magnetic field

Fig.9a indicates that disturbing magnetic field delays the armature's motion, no matter whether it strengthens or weakens the air-gap field. Furthermore, the delay time increases almost linearly along with the increment of the disturbing magnetic field, and the one weakening the air-gap field makes it increase faster.

Fig.9b shows that the pick-up time becomes longer with the increment of the disturbing magnetic field that weakens the air-gap field. With the increment of the disturbing magnetic field that strengthens the air-gap field, the pick-up time changes little.

Fig.9c indicates that the disturbing magnetic field that weakens the air-gap field makes the end pressure between armature and pole shoe decrease greatly in the pick-up position. The disturbing magnetic field that strengthens the air-gap field makes the end pressure increase, but the force grows more and more slowly with the increment of the disturbing magnetic field, which results from the saturation of the magnetic circuit. Fig.9d shows the variation of final velocity in the pick-up position disturbed by the magnetic field.

Analysis of incorrect operation

Figs.10a~10d show the dynamic characteristics when the disturbing magnetic field is −0.02 T. After 25 ms, the exciting current reaches its stable value, the attractive torque and the reaction torque are nearly equal, and the armature's velocity is approximately zero. But the displacement of the armature is only 2.285°. It has not reached the pick-up position, which means that the relay could not operate correctly in such a condition, and the armature finally stops in a place between the drop-out position and the pick-up position.

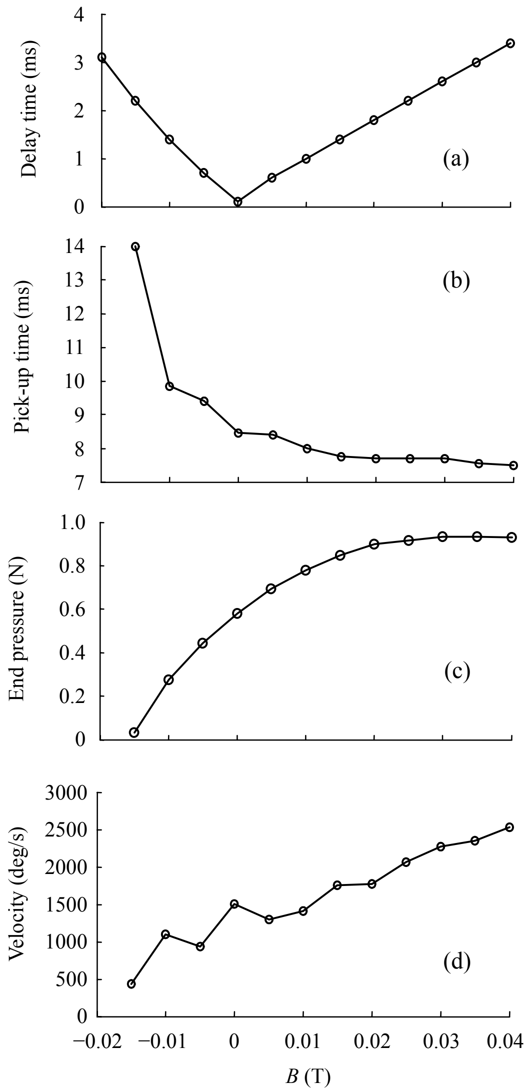

Fig.9 Delay time (a), pick-up time (b), end pressure (c), and variation of final velocity (d) vs. the disturbing magnetic field

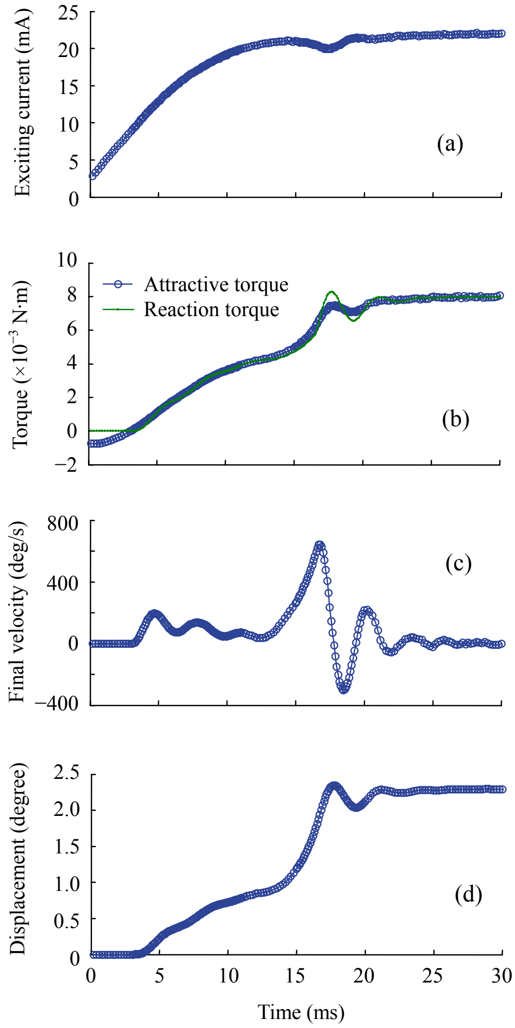

Fig.10 Exciting current (a), torque (b), final velocity (c), and displacement (d) of the armature in an incorrect-operation condition

CONCLUSION

In this paper, we compute the clapper relay's dynamic characteristics disturbed by a uniform static magnetic field by FEM. It is found that the disturbing magnetic field delays the armature's motion, no matter whether it weakens or strengthens the air-gap field in the sensitive direction. The disturbing magnetic field weakening the air-gap field has a greater effect on dynamic parameters (such as delay time, pick-up time, end pressure, and final velocity) than the one strengthening the air-gap field. When the disturbing field is −0.02 T, the armature cannot operate correctly. The method proposed in this paper can be used to evaluate the EMC of an electromagnetic relay in the static magnetic field.

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