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3D ANALYSIS OF THE BEHAVIOR OF A FOREIGN OBJECT IN ELECTROMAGNETIC RELAYS

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Summary. Even when the relay cover is damaged, foreign objects are rarely generated. A foreign object may become attracted between two contacts of the relay by electrostatic forces, potentially causing poor conductivity. Therefore, it is necessary to understand how it is attracted to the vicinity of the contacts. In this study, we numerically analyzed the behavior of a foreign object near the contacts using a numerical model. The contact force between the foreign object and the contacts was obtained using the theory of elasticity. The motions of the contacts were solved using the mode-superposition method. The electric field near the contacts was obtained using a numerical method based on the combination of the coordinate transformation and the finite difference method. It was shown that the motion of the charged object depends on the shape of the contact and the charge amount of the object.

1 INTRODUCTION

Electromagnetic relays are simple electromechanical switches that can open or close a contact through an electromagnet. More than 20 relays per automobile are used.

Although many experimental and analytical studies have demonstrated the effectiveness of electromagnetic relays [1, 2], many questions remain unanswered regarding the issue of poor conductivity caused by foreign objects. A plastic cover is placed over the relays to prevent the entry of foreign objects. However, the damage to the cover may result in the occurrence of foreign objects. When a foreign object remains on movable or fixed contacts, poor conductivity occurs. Iida et al. [3] presented a dynamics simulation method for a charged foreign object on the fixed contact. Since they particularly focused on the two-dimensional behavior of the foreign object, the relationship between the shape of the relay and the motion of the charged foreign object was not examined.

In this study, we numerically analyzed the three-dimensional behavior of a foreign object near contacts using a numerical model. The contact force between the foreign object and the contacts was obtained using the theory of elasticity. The motions of the contacts were solved using the mode-superposition method. The electric field near the contacts was obtained by a numerical method based on the combination of the coordinate transformation and the finite difference method. The behavior of the charged object was calculated by the Runge–Kutta method. It was shown that the motion of the charged object depends on the shape of the contact and the charge amount of the object.

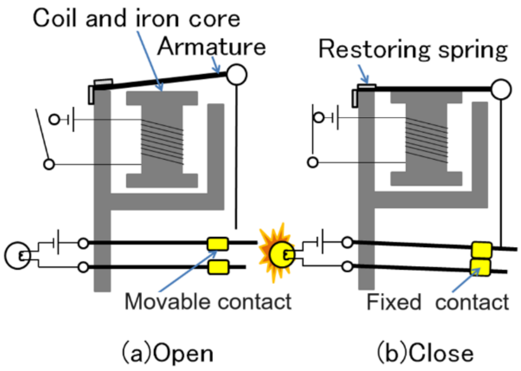


Figure 1: Electromagnetic relay

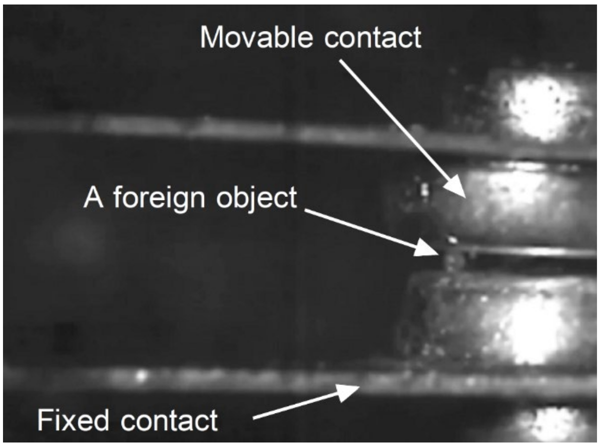


Figure 2: A foreign object and the contacts

2 ELECTROMAGNETIC RELAY

Figures 1(a) and (b) show the electrical circuit of the relay in the off and on states, respectively. When the switch is turned on, current flows through the coil, and the electromagnetic force pushes the armature down onto the movable contact. Then, the movable and fixed contacts are closed, allowing current to flow and causing the bulb to turn on. When the switch is turned off, the movable contact returns to its original position, causing the bulb to turn off. A plastic cover is placed over the relays to prevent the entry of foreign objects. However, when the relay cover is damaged, foreign objects may enter, although rarely.

Figure 2 shows a foreign object remaining on the fixed contact. When the object is sandwiched between the two contacts, the current does not flow. As shown in Figure 1(a), voltage is applied to the movable contact even when the switch is off. As the fixed contact is grounded, an electric field is generated between the two contacts. If the foreign object is charged, it may be attracted towards either contact owing to the electrostatic force, resulting in poor conductivity.

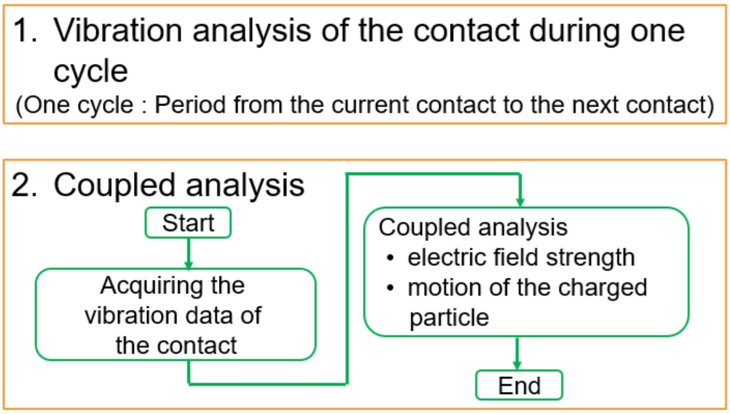


Figure 3: Flowchart used in this study

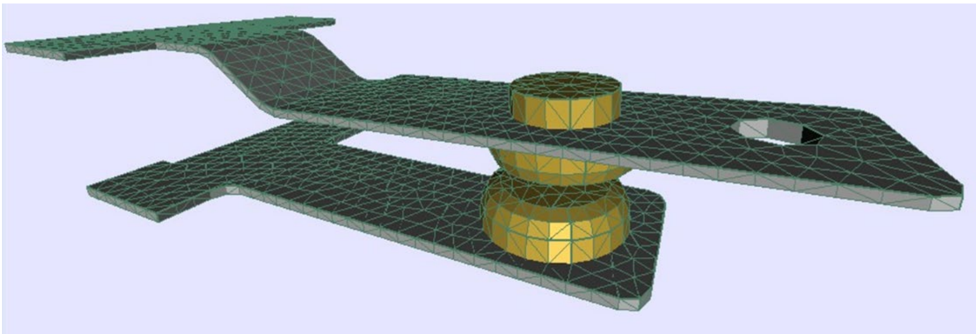
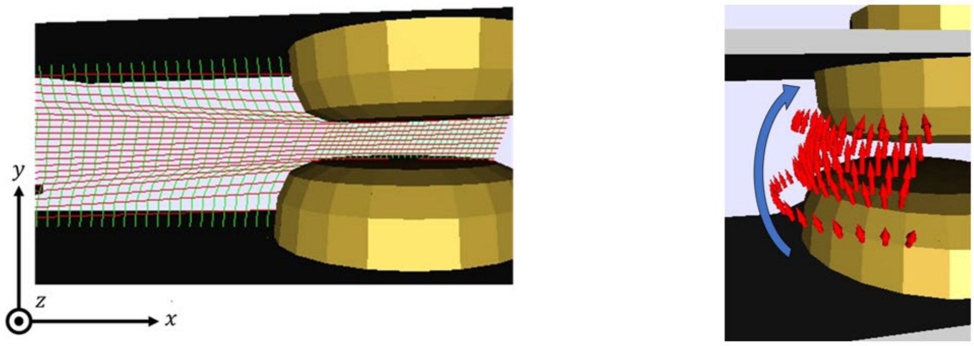


Figure 4: FEM mesh for the contacts

3 NUMERICAL APPROACH

The foreign object (hereinafter, referred to as the charged particle) moves between contacts and collides with either of two contacts. Additionally, when the movable contact returns to its original position, the two contacts vibrate. Therefore, to analyze the motion of the charged particle, it is necessary to conduct the analysis of the electric field between the two contacts, the vibration analysis of the contacts, and further motion analysis including collisions of the charged particle with the contact. However, the calculation cost is high. On the other hand, since the charged particle is assumed to be very small, it is considered that the collision of the charged particle with the contact does not have a significant impact on the vibration behavior of the contacts. In this study, vibration analysis was conducted before any other analysis.

Figure 3 shows the flowchart of analyses conducted in this study. First, the vibration of the contacts during one cycle was analyzed, where one cycle refers to the time it takes for two contacts to make contact again. After acquiring the vibration data, the other analyses were conducted simultaneously.



(a) Region analyzed between the two contacts (b) Electric field vector

Figure 5: Analysis of the electric field

The vibration of the contacts was analyzed by the finite element method. The geometry domain for mesh generation is divided into polygon-type sub domains, as shown in Figure 4.

The equation of motion for the contact is given by

$$[M]\{\ddot{u}\} + [K]\{u\} = \{0\}, \tag{1}$$

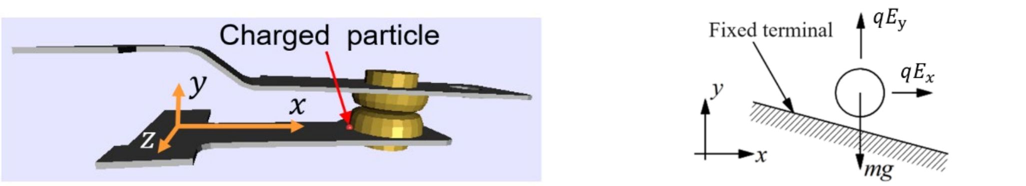
where $[M]$ and $\{u\}$ are the mass matrix and displacement of each node, respectively. $[K]$ is the stiffness matrix.

Using Eq. (2), we can transform Eq. (1) into Eq. (3).

$$\{u\} = [\Phi]\{\xi\} \tag{2}$$

$$[M^*]\{\ddot{\xi}\} + [K^*]\{\xi\} = \{0\} \tag{3}$$

where $[\Phi]$ and $[M^*]$ are the modal and modal mass matrices, respectively, and $[K^*]$ is the modal stiffness matrix.



(a) Contacts and a particle (b) Electrostatic force acting on a particle

Figure 6: Charged particle on the fixed contact

Since the shape of the contacts is complex, we simplified the region analyzed using the coordinate transformation. The electric field strength was analyzed by the finite difference method. Figures 5(a) and (b) respectively show the region analyzed between the two contacts and the electric field vector. As shown in Figure 5(b), it is understood that a positively charged particle may be attracted toward the movable contact through the electrostatic force.

Figures 6(a) and (b) show the charged particle on the fixed contact and the electrostatic force acting on the particle, respectively. In this study, the charged particle was assumed as a sphere. Therefore, the equation of motion for the charged particle is given by

$$\left.\begin{aligned} m\ddot{x} &= qE_x \\ m\ddot{y} &= qE_y - mg \\ m\ddot{z} &= qE_z \end{aligned}\right\}, \qquad (4)$$

where m and q are the particle mass and the amount of charge, respectively. E_x, E_y and E_z are the strengths of the electric fields in the x-, y- and z- directions, respectively.

Figure 7 shows the behavior of the charged particle obtained by numerical analysis. The contact force between the foreign object and the contacts was obtained using the theory of elasticity.

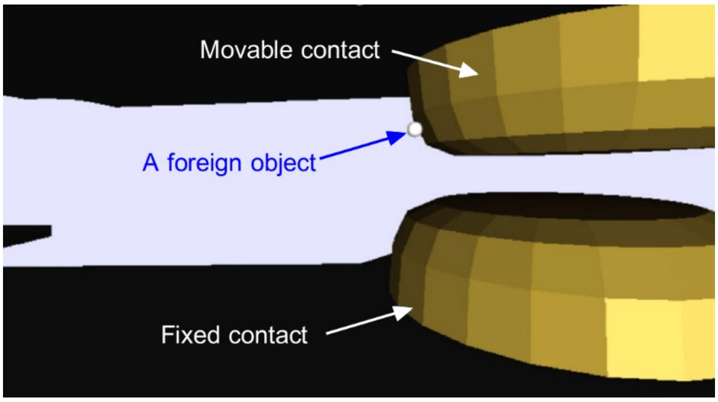
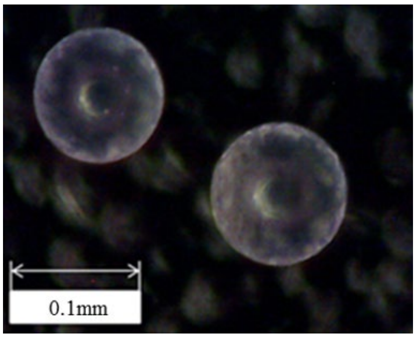
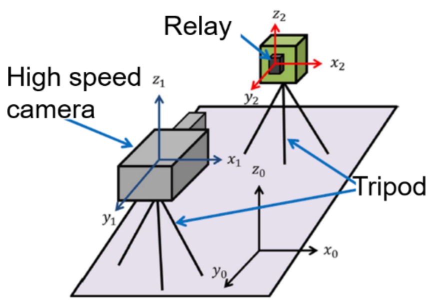


Figure 7: Behavior of the charged particle



(a) Spherical particles



(b) High-speed camera and relay

Figure 8: Experimental apparatus

4 EXPERIMENT

To verify the validity of the numerical model, experiments were conducted. Figures 8(a) and (b) show the plastic particles used in this study and the experimental apparatus, respectively. The behaviors of the charged particle and the contacts were captured by a high-speed camera. We ensured that the charging condition of the plastic particles was kept as consistent as possible in across all experiments. First, the plastic particles were stored in a container with a relative humidity of 70% or higher for 24 h to discharge them. The charge amount of the particles was measured in each experiment using a digital electrometer and a Faraday cage system.

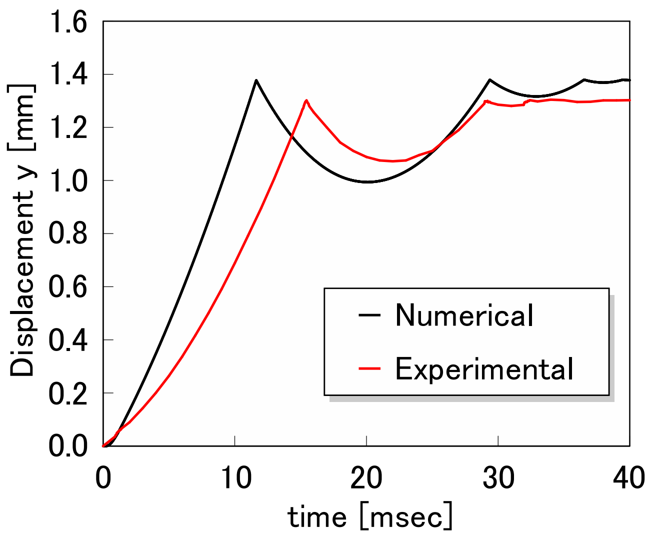


Figure 9: Numerical and experimental results

5 NUMERICAL SIMULATION RESULTS

In Figure 9, the relationship between the y-axis displacement of the charged particle and the time obtained by numerical simulation is compared with that measured in each experiment. It is shown that the particle moves upwards against the gravitational force and repeatedly collides with the movable contact. The numerical simulation result is roughly in agreement with the experimental result.

Figure 10 shows the numerical simulation results for the time history of the y-axis displacement. This figure also shows the effect of the charge amount of the particles on the time history of the y-axis displacement. It is shown that a highly charged particle collides with the movable contact, whereas a poorly charged particle collides with the fixed contact. Therefore, the shape of the relay and the charge quantity of the object affect the motion of the charged particle.

6 CONCLUSIONS

The three-dimensional behavior of a foreign object near the contacts of the relay was analyzed using a numerical model. In the numerical simulation, the analysis of the electric field between the two contacts, the vibration analysis of the contacts, and further motion analysis including collisions between the charged particles and contacts were conducted. The numerical simulation result was roughly in agreement with the experimental result. Moreover, it was shown that the motion of the charged foreign object depends on the shape of the contact and the charge amount of the object.

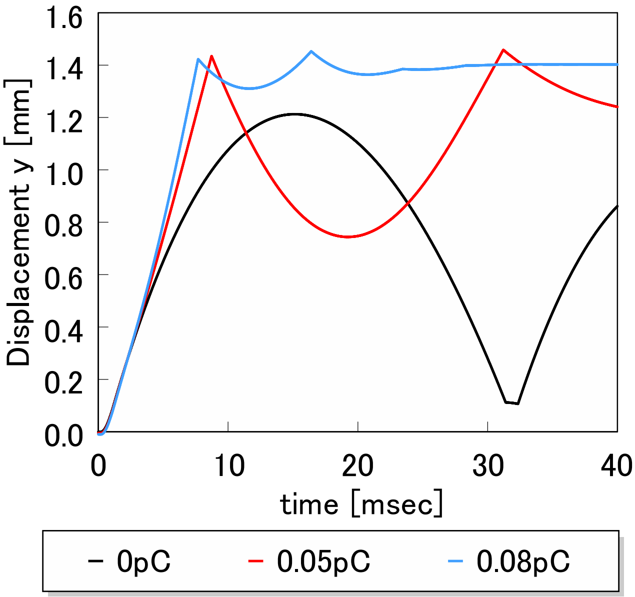


Figure 10: Effect of the charge amount on the behavior of the particle

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