Analysis of Variable Stiffness Magnetorheological Elastomer Employing Particle Method and FEM

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Magnetorheological elastomers (MREs) are composed of silicone and iron powder so that they can possess ferromagnetic and viscoelastic properties. The shape and the stiffness of the MREs change depending on the magnetic field [1]. Therefore, it is expected to be used for an artificial muscle or damping material [2] [3]. However, it is difficult to design because ferromagnetic and viscoelastic properties greatly change depending on ratio of the iron powder and strength of magnetic field. This paper presents a numerical method for MREs analysis by coupling a particle method with a finite element method (FEM), in which The MRE's stiffness change according to the magnetic field was taken into account. The numerical algorithm is described and calculated results are shown.

***Index Terms*— Particle method, Finite element method, Magnetorheological Elastomer, Magnetic forces,**

I. INTRODUCTION

THE MRE's property changes according to the ratio of the silicone elastomer to the iron powder. Additionally, MRE deformation is a very complicated phenomenon since magnetic circuit deformation also simultaneously occurs. Therefore it is difficult to make a guide for designing MRE soft devices. We need analysis method that can calculate MREs behavior and magnetic field at same time. Traditional analysis method for flexible materials has been proposed by many researchers, including the FEM. FEM is suitable method to calculate electromagnetic field. However, it is not effective to calculate large deformation of the object. This is because special processing is necessary for protection of mesh. One of the solutions for the problem is the employment of a meshfree method such as the particle method [4][5]. This paper proposes an analysis method for the calculation of MRE behavior by coupling the particle method with FEM, in which the nonlinearity of MREs as Young's modulus, Poison's ratio is taken into account.

The purpose of this paper is to validate this coupled analysis method through the comparison with experimental results.

II. GOVERNING EQUATIONS

The equation of motion of viscoelastic bodies is described in (1). All the materials are assumed isotropic[6].

$$\frac{\partial v_k}{\partial t} = \frac{1}{\rho}\frac{\partial}{\partial x_l}\left(\lambda \varepsilon_{mm}\delta_{kl} + 2\mu\varepsilon_{kl} + 2\eta\dot{\varepsilon}_{kl}\right) + K_k \qquad (1)$$

Here, x_l is the particle coordinate, v_k is the particle velocity, ε_{kl} is the strain, $\dot{\varepsilon}_{kl}$ is the strain rate and K_k is the acceleration by the external force as electromagnetic force and gravity. ρ and η are the density and viscous coefficient of the elastomer respectively and δ_{kl} denotes Kronecker delta. The subscript *k, m*, and *l* indicates the dummy index of tensor. λ and μ are Lame's constants as shown in (2)

$$\lambda = \frac{E\nu_E}{(1+\nu_E)(1-2\nu_E)}, \quad \mu = \frac{E}{2(1+\nu_E)} \qquad (2)$$

Where E is Young's modulus and ν_E is Poisson's ratio. Young's modulus and Poisson's ratio are given from a result of measurement of MRE as the strain function.The governing equation of a magnetic field is expressed in (3).

$$\mathrm{rot}(\nu_M \,\mathrm{rot}\boldsymbol{A}) - J_0 = 0 \qquad (3)$$

Here*,* $\boldsymbol{A}$ is the magnetic vector potential, *and* J_0 is the forced current. ν_M is the reluctivity. In this method, the electromagnetic force obtained from equation (3) is substituted into equation (1) as the external force.

III. COUPLED ANALYSIS METHOD AND ANALYSIS FLOW

The viscoelastic material is expressed as an aggregate of finite particles (calculation points) into particle method. Each particle possesses physical quantities such as mass and velocity.

The deformation of the analyzed model is determined by calculating the movement of each particle using equation (1). The external force in equation (1) is calculated by FEM. The flow of the analysis method is as follows (Fig. 1).The particle coordinates of the magnetic body are converted to the nodal point coordinate information in FEM.

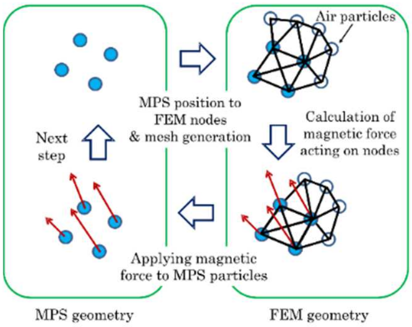


Fig. 1 Conversion of particle data and nodal point data

IV. ANALYZED MODEL

Fig. 2 shows the analyzed model. This model consists of an MRE, silicone and an electromagnet. The silicone and MRE are placed on an acrylic plate, and the electromagnet is placed under that plate. A current is applied to the electromagnet and the behavior of the MRE is obtained.

Analysis condition is shown in Table 1. Additionally, Young's modulus and Poison's ratio that are using in this paper is shown in Fig. 3. And, applied current range is from 0A to 2.5A.

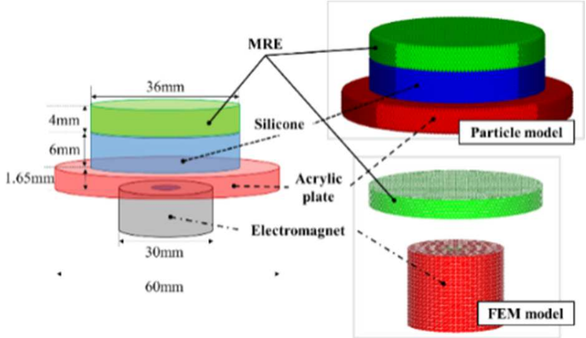
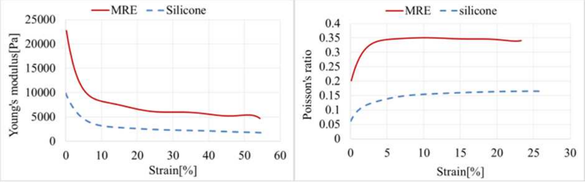


Fig. 2 Analyzed model

Table 1
Analysis conditions and discretization data

Density of MRE [kg/m3]	2.97×10^{3}
Density of silicone [kg/m3]	0.99×10^{3}
Relative permeability of MRE	2.0
Core's magnetic permeability	2500
Initial interparticle distance[m]	1.0×10^{-3}
Initial time step [s]	1.0×10^{-5}
Number of particles in MPS	56,352
Number of element in FEM	263,000



(a) Young's modulus (b) Poisson's ratio

Fig. 3 Young's modulus and Poisson's ratio

V. EXPERIMENTAL MODEL

Fig. 4 shows the experimental model. KE-1052 silicone (Shin-Etsu Silicone Co.) and CS carbonyl iron (BASF Japan Co. Ltd.) were used. Fig. 5 shows the measurement system. The center of the upper surface of the MRE is measured using a laser displacement meter.

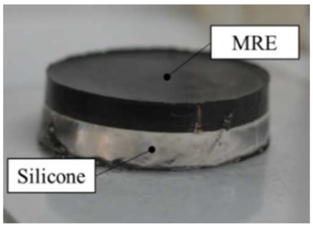


Fig. 4 Experimental model

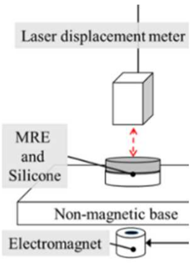


Fig. 5 Measurement system

VI. COMPARISON OF ANALYSIS AND EXPERIMENTAL RESULT

Fig. 6 shows result of previous analysis, new analysis and experiment. Gradient of previous analysis curve is larger than experimental curve. It is considered that MRE's stiffness is changed by force of magnetic field [7]. Previous analysis method had not taken into account the stiffness change by a force of magnetic field. Therefore, a stiffness change by the force of the magnetic field was introduced into this analysis by calculating interparticle force. Interparticle force is calculated by magnetic moment of each particle and external magnetic field (4).

$$\boldsymbol{F}_i = \mathrm{grad}(\boldsymbol{M}_i \cdot \boldsymbol{H}_i) \tag{4}$$

Here, $\boldsymbol{F}_i$ is force of the focused particle i. $\boldsymbol{M}_i$ is magnetic moment. $\boldsymbol{H}_i$ is the external magnetic field which each particle made the location of particle i.

It became evident that gradient of analysis curve was suppressed due to interparticle force by a force of magnetic field. This is because interparticle force was heightened with increasing magnetic force. By analysis result of added force (Fig. 6), it proved that Displacement was suppressed in the high magnetic field range.

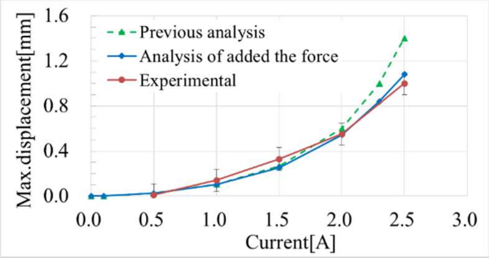


Fig. 6 Before it's introduced

VII. CONCLUSION

In this paper, the analysis result which considered interparticle force and experimental result were compared. Then, the validity of the analysis method which considered interparticle force by a magnetic field could be confirmed. In final paper, comparison of analysis and experiment result in changing magnetic field will be shown. And the validity of this analysis method is described.

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