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Full-field deformation of magnetorheological elastomer under uniform magnetic field

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A digital holographic interferometry was applied to analyze the morphology transformation of the magnetorheological elastomer, and both the contraction and stretch deformation were observed under applying an external magnetic field on the sample. Both isolated particles and grouped particles were observed in the magnetorheological elastomer sample, and these two kinds of particles resulted in the concave-convex deformation of the sample. The deformation of magnetorheological elastomer was calculated by using a 2D finite element model, and the results agreed well with the experimental analysis. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4722789]

Magnetorheological elastomers (MREs) are composites consisting of ferromagnetic particles embedded in nonmagnetic rubber-like matrix. Their properties, such as elastic modulus, damping, magnetostriction, and electrical conductivity, can be controlled by an external magnetic field.[1–5] Due to these controllable properties, MREs have been widely used in vibration absorber, isolator, engine mounts bushing, actuator, etc.[6,7] Among these applications, MRE is often used as a bearing element. Therefore, its deformational property under an external magnetic field is the key issue to ensure the applications.[8–10]

The deformation of MRE in response to an external magnetic field results from the complex magnetic interactions between particles and mechanical interactions between particles and rubber-like matrix. Although many works have been focused on investigating the deformational property of MRE, the as-obtained research results were contradictive when comparing the experiments and theories. Ginder[11] and Guan[12] reported the field-structured MRE would stretch when exposed to magnetic field in their experiments. However, Zhou[13] found the field-structured MRE would compress along the direction of the magnetic field. Besides, some other researchers found that random-filled MRE would stretch along the direction of magnetic field.[12–16] When the experimental results are tried to be compared with the theory prediction, striking contradiction appears. Borcea[17] noted that the random filled MRE would expand along the applied magnetic field while field-structured MRE would compress. Differently, Wood[18] predicted both field-structured MRE and random filled MRE would contract along the direction of magnetic field using Monte Carlo simulation. Morozov[19] thought the deformation of random filled MRE is dependent on the aspect ratio of the sample, i.e., MRE would shrink if the aspect ratio is larger than the critical value and stretch if the aspect ratio is smaller than the critical value. Obviously, the researchers can not reach an agreement on the experimental results and theoretical analysis. Therefore, the deformational property of MRE in uniform magnetic field needs to be further investigated.

The difficulty involved in measuring the deformation of MRE in uniform magnetic field is significant. Some methods have been proposed to investigate the deformational property of MRE.[11–14] However, these methods have many disadvantages. For example, attaching strain gauge to the surface of MRE alerts the field-induced deformation,[11,12] and the capacitive method needs robust contact between the movable capacitor plate and MRE surface.[14] In addition, all the reported methods for measuring the deformation of MRE cannot measure the full-field deformation of MRE. The measuring result is just the deformation of one point on MRE surface or the average deformation of a surface.

In this work, a digital holographic interferometry was invited to analyze the full-field deformation of MRE in uniform magnetic field. The results would be benefit to a deeper understanding of MRE. A random-filled MRE based on carbonyl iron particles (Type CN, with the average diameter 6 μm, provided by BASF Co., Germany), HTV silicone rubber (Type: MVQ 110-2, from Dong Jue Fine Chemicals Nanjing Co. Ltd), vulcanizing agent (double methyl double benzoyl hexane, from Shenzhen Gujia Co.), and Di-(2-ethylhexyl)phthalate (from Shanghai resin factory Co. Ltd.) were prepared with the dimension of $\Phi 20 \times 10$ mm. The mass fraction of carbonyl iron particles was 60%. To observe the deformational property of MRE, digital holographic interferometry was used to measure the out-of-plane deformation of MRE sample for its high precise, non-contact, and full-field measuring. The resolution of digital holographic interferometry can reach as tiny as tens of nanometers.[20]

Fig. 1 shows the schematic diagram of the measuring system and the arrangement of MRE sample. The laser light used in the experiment was He-Ne laser with the wave length of 632.8 nm. The resolution of the CCD camera was 1624×1236 pixels. The MRE sample was placed in a uniform magnetic field which was generated by a magnetic coil and parallel to the axis of the cylindrical specimen. Besides, the magnetic flux density was set at 50 mT to make it reasonable to distinguish the contraction deformation from the stretch deformation of MRE sample. The whole measuring

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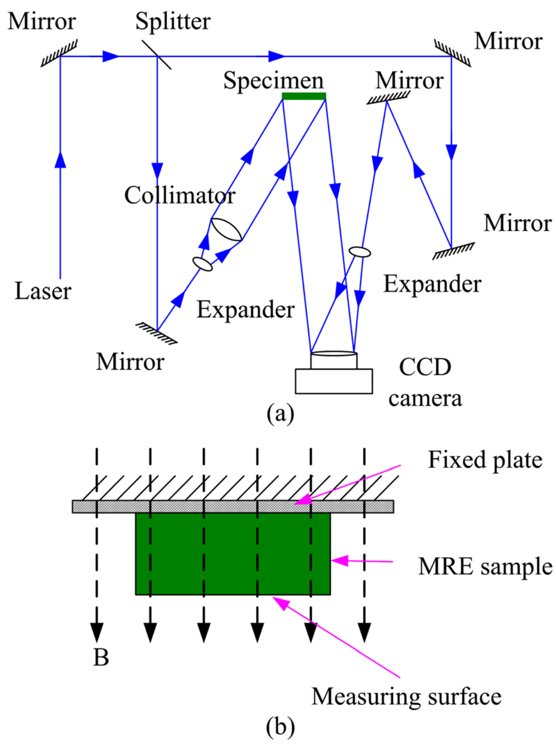

FIG. 1. Schematic diagram of digital holographic interferometry for measuring the out-of-plane deformation of MRE; (a) optical pathway diagram; (b) arrangement of MRE sample.

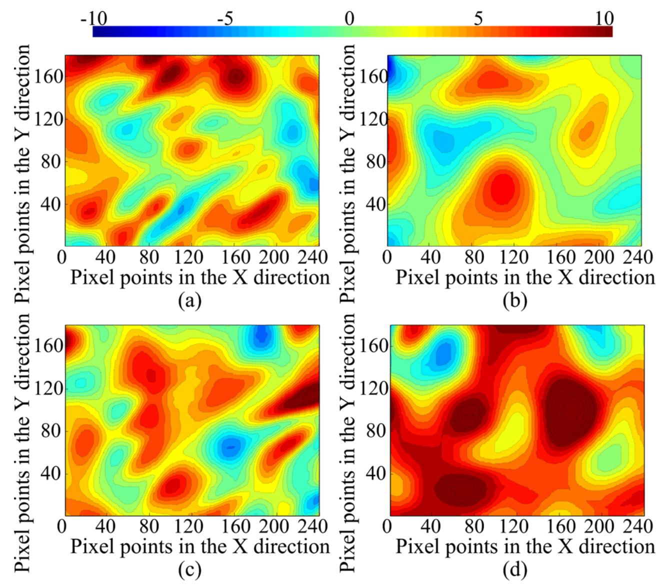

FIG. 2. Out-of-plane deformation of MRE samples; (a), (b), (c), and (d) represent different MRE samples, respectively.

system was fixed on a vibration isolation platform to prevent the vibration caused by the ground base. The CCD camera captured images before and after the deformation of MRE sample. By analyzing the phase difference of the two images, the full-field out-of-plane deformation of MRE can be obtained.

In measuring of the out-of-plane deformation of MRE, one circular surface of the sample was glued to the fixed plate (Fig. 1(b)), and the other surfaces were free to move. During the measuring, tens of MRE samples were measured, and the experimental results were similar. To show the experimental results clearly, four of them are presented in Fig. 2, where the x and y axes represent the pixel points in the x direction and y direction, respectively, i.e., the length and width of the MRE samples, respectively. It is worth to be mentioned that the shape of MRE sample during the measuring is a cylinder. However, to show the results more clearly, a rectangle part from the circular surface of the measuring sample was chosen to be shown in Fig. 2. The color map in Fig. 2 indicates the values and directions of the out-of-plane deformation. The numbers beside the color map are the dimensionless deformation values rescaled by the minimum deformation which was measured by the experiment. The positive values mean the direction of the deformation is the same with the outer normal of the measuring surface (Fig. 1(b)), while the negative values mean the opposite direction. Figs. 2(a)–2(d) show the out-of-plane deformation of four MRE samples, respectively. The red parts indicate the deformation of MRE is along the direction of the outer normal, i.e., the deformation is stretch, while the blue parts show the contraction deformation. As shown in Fig. 2, the maximum values of the stretch deformation and the contraction deformation reach nearly 10, respectively. The maximum difference of the two kinds of deformation reaches nearly 20, which is far beyond the minimum deformation. Therefore, the experimental results are reasonable. Comparing Figs. 2(a)–2(d), the distributions of the contraction and the stretch deformation are different from each other mainly due to the random distribution of carbonyl iron particles. The experimental results in Fig. 2 are quite different from the previous reports by other researchers.[11–16] In previous report, only contraction deformation or stretch deformation could be observed on one MRE sample. This is mainly due to the limitation of their measuring method which could only give the deformation of one point on MRE surface or the average deformation of a surface. Therefore, the details of the full-field deformation of the surface of MRE sample can not be observed. In our study, both the contraction deformation and stretch deformation are observed in the same MRE sample, which would be benefit to a deeper understanding of MRE.

For the practical MRE, iron particles cannot be uniformly distributed or form ideal chain-like structures. Both isolated particles and grouped particles should exist in the MRE sample. Fig. 3 shows the microstructure of the MRE sample measured by scanning electron microscope (model XL-30 ESEM, Philips). It can be seen that some particles are

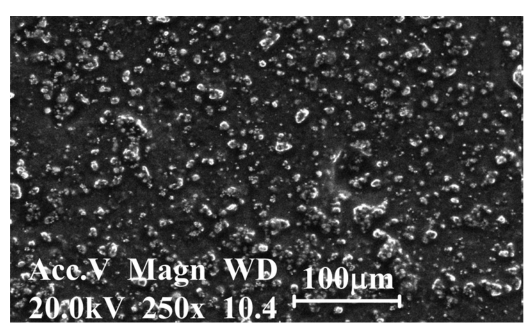

FIG. 3. SEM image of MRE sample.

isolated and some are grouped. Stolbov[8] noted that the isolated particles result in the contraction deformation of MRE and the grouped particles result in the stretch deformation when uniform magnetic field is applied on MRE. The two kinds of iron particles have opposite effect on the deformation of MRE. Therefore, in practical MRE, the deformation of a surface is concave-convex, as shown in Fig. 2. Besides, the isolated particles and the grouped particles are distributed randomly. And, thus, the distribution of the stretch deformation and the contraction deformation should be random, which is shown in Fig. 2.

To further investigate the concave-convex deformation of MRE, a 2D finite element model is used to carry out the numerical analysis. The calculation is carried out on a rectangular elastic matrix filled with 200 spherical particles. To simplify the calculation, the particles are glued to the matrix, and the relative permeability of the matrix is set to 1. From the viewpoint of mechanics, the elastic modulus of the particles is assumed to be much more rigid than the matrix (1000 times the elastic modulus of the matrix). The boundary condition is chosen in such a way that the bottom of the rectangular model is fixed and the other boundaries are free to move. Besides, the mesh is made sufficiently dense so that each iron particle contains enough nodes inside.

Three MRE samples, i.e., MRE with only isolated particles, MRE with only grouped particles, and MRE with both isolated and grouped particles were used to carry out the numerical analysis. A constant magnetic field was imposed along the direction shown in Fig. 4. The calculated out-of-plane deformation of the top surface, i.e., the deformation of the top surface along the direction of the magnetic field, is shown in the bottom of Fig. 4, where the dotted line and the solid line represent the undeformed surface and deformed surface, respectively. Fig. 4 demonstrates that isolated particles results in the contraction deformation and grouped particles results in the stretch deformation. In practical MRE, both isolated particles and grouped particles exist. Therefore the calculated deformation of a MRE surface is concave-convex which agrees well with the experimental results shown in Fig. 2 and the assumption proposed by Stolbov.[8]

In conclusion, the deformation of MRE when exposed to a uniform magnetic field is dependent on the distribution of the iron particles. Isolated particles lead to the contraction deformation of MRE and grouped particles lead to the stretch deformation. Therefore, the out-of-plane deformation of a surface of MRE should be concave-convex. In this research, using holographic interferometry, the full-field out-of-plane deformation of a surface of MRE is measured. Both contraction deformation and stretch deformation are observed in the same MRE sample, which agrees well with the Stolbov's assumption. Using a 2D finite element model, the deformation of MRE was calculated, and the results agree well with the experiment.

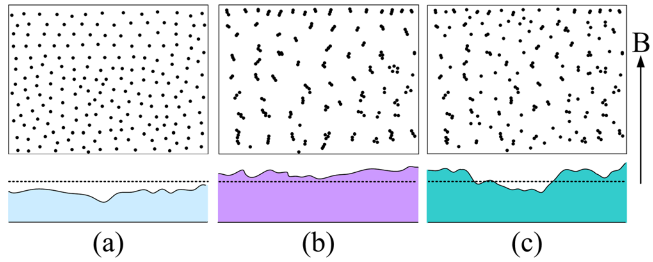

FIG. 4. 2D finite element model (up) and the calculated out-of-plane deformation (down); (a) MRE with isolated particles; (b) MRE with grouped particles; (c) MRE with both isolated and grouped particles.

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