Bio-mimic Motion of Elastic Material Dispersed with Hard-magnetic Particles

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Recently, many researches on biomimetics have been reported, in which soft motions of natural creatures have also been targeted. Among them, cilia are attracting natural soft organ, which is an effective fluidic system in the natural world. Cilium is a simple hair-like organ; however, it works in a non-simple way. For example, beating pattern of natural cilium consists of 2 types of different stroke patterns; effective stroke and recovery stroke. We focused on a cilium as our target as a simple cantilever of a soft elastic material. We have already developed artificial cilia with magnetic elastomers. In this research, we compared cantilever beams with soft- and hard- magnetic particles. In this paper, we performed 2 experiments to compare the characteristics of cantilevers with 2 types of magnetic powders. In the first experiment, we utilized neodymium magnets that could be controlled the angle in order to observe the motion of beams in the static state. The latter one, we actuated beams in rotating magnetic fields to obtain dynamic behavior of an artificial cilium. As a result, we showed some differences between soft- and hard- magnetic materials.

Keywords: Elastomer, Magnetic particles, Soft actuator, Bio-mimic, Artificial cilium

1. Introduction
Recently, many researches on biomimetics have been reported. Super-hydrophobic surface on lotus leaves [1] and adhesive surface structures on soles of geckos [2] are famous examples. Soft motions of mollusks such as snails, slugs, and octopuses, have also been targeted in recent years. Cilia are also attracting natural soft organ, which is an effective fluidic system [3-6] in the natural world that are widely observed on surfaces of microorganisms. For example, Paramecium can swim using cilia surrounding its body surface as shown in Fig. 1. The trachea inner surface of mammals is also popular example, which can move out dusts and viruses from our body.

We focused on these cilia as our target. If we could apply biomimicry structures of these natural cilia, they would be useful engineering tools. We utilized magnetic elastomer [7-9] to mimic the motion of flexible structures in natural cilia [10-20].

As we have already shown in previous researches, ciliary movement is asymmetric [15-24]. The stroke pattern of a natural cilium consists of 2 different strokes; the effective stroke and the recovery stroke.

Figure 2 schematically shows this asymmetric pattern. We have already realized these different stroke patterns on our artificial cilium using a
rotating magnetic field.

There are 2 kinds of magnetic particles, soft- and hard- magnetic particles. In our previous works, we employed a rubber material dispersed with soft magnetic particles. Soft magnetic material is magnetized only under an applied magnetic field, while, hard magnetic material keeps its magnetized state even out of the magnetic field. Permanent magnets are typical hard magnetic material.

In this paper, we tried to employ hard magnetic particles for artificial cilia. Figure 3 shows a simple schematic image of actuations. We prepared 2 kinds of beam samples as shown in Fig. 3(a). Both samples had different inner structures. For the soft magnetic particles, we set chain-like particle clusters in the structure. We can change magnetic orientation by this chain clusters. In this work, we set chain-clusters perpendicular to the beam. For hard magnetic particles, we set N- and S- poles to left and right sides of the beam, respectively. The both beams could be actuated by a rotating magnetic field as a bio-mimic motion of a natural cilium. Therefore, we can control the deformation of the shaped object by utilizing the difference in the behavior due to the magnetic anisotropy. After curing, the chain clusters were fixed in the elastic medium that set magnetic anisotropy. Magnetic particles has different angle of magnetic anisotropy and different behavior depending on, soft- or hard- magnetic particles.

Soft magnetic particle: These chain clusters will cause the rotational moment to be parallel to the magnetic flux line under an applied magnetic field. Hard magnetic particles: Each particle has a magnetic polarity, and each particle cause the rotational moment parallel to the flux lines.

In this research, in order to show the difference in the behavior of soft- and hard- magnetic particles, cantilever beams utilizing each magnetic particle were fabricated, and the motion was evaluated.

Fig. 2. Asymmetric ciliary movement; effective and recovery strokes.

Fig. 3. Schematic images of setup for actuation. The angle of the applied magnetic field can be changed as rotating the sets of permanent magnets from initial state (a) to specific angle (b).

2. Materials

We employed magnetic elastomer for these experiments. We utilized siloxane elastomer (ecoflex 0030, Smooth-On Inc.) as base material. We prepared 2 kinds of materials, soft- and hard-magnetic particles to be dispersed into the elastomer. We chose carbonyl iron particles (median diameter: 4.36 μm) for soft magnetic material, and Sr-ferrite particles (average particle diameter: 1.40 μm, SF-500, DOWA F-Tec) for hard magnetic one. The magnetic particles were dispersed at the rate of 3 vol%. All materials were mixed by a planetary centrifugal mixer (Kakuhunter, Shashin Kagaku CO., Ltd.).

We prepared magnetic cantilevers. Each cantilever was cut from magnetic sheets which had magnetic anisotropy perpendicular to plains. First, we formed magnetic sheets of magnetic elastomers. Two kinds of materials were set between 2 acrylic plates with keeping a gap of 250 μm using spacer
sheets. For soft magnetic material, we applied magnetic field of 20.6 mT for 2 hours and cured in room temperature to generate chain clusters. For hard magnetic material with ferrite particles, each cured sheet was magnetized using a coil of vibrating sample magnetometer (VSM) at the magnetic field of 5 kOe. We cut out cantilever from the sheets. All cantilevers were set on a PDMS block to be the length of 3 mm.

3. Static deformation of magnetic cantilever

In this section, we show results about static deformation of the magnetic cantilevers. We utilized 2 neodymium magnets to apply a uniform magnetic field. Figure 4 shows the experimental apparatus. The cantilever was set at the center of the apparatus, and the magnets were set on both sides of a cantilever and the angle of the magnets could be controlled. The angle was changed every 15 degrees from -180 to 180 degrees. The cantilever was set standing between the 2 permanent magnets, and the direction of the magnet was set 0 degree to horizontal direction as initial condition. Magnetic flux density was set at 20, 40, and 60 mT.

Figure 5 shows images of actuated sample beams. Figures 5(a) and (b) show samples dispersed with carbonyl iron particles and ferrite particles, respectively. The images of deformation depending on each angle of applied magnetic field were superimposed into one image. The range of deformation increased as increase of applied magnetic field, and the beam with ferrite deformed in wider ranges than that with carbonyl iron. Figure 6 shows the relationship between angle of applied magnetic field and displacement of each beam. The beam with carbonyl iron particles less deformed in low magnetic fields, while the beam with ferrite particle deformed larger overall. In addition, there was much more difference between the behaviors of the both samples. The deformation pattern of the soft-magnetic beam changed every 180° period, and the beam with ferrite particles did every 360°.

4. Dynamic behavior of magnetic cilium

We actuated the beams in rotating magnetic fields to observe the difference between dynamic and static states. Experimental setup is shown in Fig. 7. We utilized the same samples used in the previous experiment. Each sample was placed on the stage and was driven by a rotating magnetic field of 60 mT. We changed the rotational speed and observed dynamic motion. We changed the rotational speed from 50 to 500 rpm for the sample with the carbonyl iron particles and 500 rpm for the sample with the ferrite particles.
iron particles, and from 100 to 800 rpm for the sample with the ferrite particles. We used a high-speed camera (VW-9000, Keyence) for observation.

Figure 8 shows samples driven by rotating magnetic fields. Snapshots were superimposed into each image. The amplitude did not change even if the rational speed increased. This result shows that the motion of samples followed the rotation of the magnetic field. The beam with the carbonyl iron particles beat 2 times in every rotation of the magnetic field. The beating frequency of the beam with the carbonyl iron in the 49 rpm magnetic field was similar to that with the ferrite particles in the 101 rpm magnetic field. Comparing the carbonyl and ferrite beams, the amplitude of the ferrite beam was larger than that of the carbonyl iron beam.

The amplitude was plotted in Fig. 9. The amplitude was still large even in high frequency area, more than 10 Hz, which was similar to the beating frequency of natural cilia. The amplitude in the dynamic motion was smaller compared to that observed in the static experiment, because of the viscous behavior of the beam material.

It should be also noted that the obtained dynamic motion did not show asymmetric beating patterns. The asymmetric motion would appear if longer beam was used for the same experiment.

5. Conclusion
In this research, Sr-ferrite particles were evaluated for high responsive magnetic elastomer. We performed static and dynamic tests, and it was found that the Sr-ferrite showed better characteristics. The Sr-ferrite could be a candidate for the next magnetic soft actuator material.

We are now developing a new 3D printing system for magnetic gels or elastomers [17,20,21]. We will try to apply the ferrite material in our future work.

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References