# FABRICATION OF SILICON RUBBER - FERROFLUID COMPOSITE ACTUATOR

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**ABSTRACT**

Magnetic nanoparticles in carrier liquid show normal liquid-like behavior. These ferrofluids show the smart property of controlling viscosity with a magnetic field. Many industries have full potential application for this ferrofluid, including the medical. The application of ferrofluid at nano-micro size structure gives improvement in efficiency and functionality. This research has focused on the development of micro-size transducers using ferrofluid, which will replace the existing mechanical system. These transducers will have key features of compact size, quick response time, and low operational cost. The micropump design was tested with latex elastomer, synthetic rubber, and silicone rubber as a diaphragm. This research has successfully developed a silicone rubber ferrofluid composite cantilever at the micro-scale. Every sample's deflection under various magnetic fields is compared. Experiments reveal that the anisotropic sample yields the largest deflection. A low magnetic field of 15mT is used to test cantilevers with a diameter of 0.4mm and a length of up to 10 mm. The highest deflection we measured at 44 mT magnetic field was 82.5 degrees. An isotropic sample exhibits a greater range of amplitude in dynamic testing. These cantilevers have two uses: as actuators and as sensors.

***Keywords:*** *Magnetic nanoparticles, ferrofluids, magnetic field.*

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## 1. INTRODUCTION

Micro-manufacturing is a rapidly growing field, particularly in the development of transducers, which are devices that convert one form of energy into another. As technology advances, there is a significant push towards miniaturization, driving the need for transducers to be developed at the micro and nano scale. These transducers, commonly referred to as Micro-Electro-Mechanical Systems (MEMS), are increasingly used in various applications, including sensors, actuators, and medical devices, where compact size, quick response, and low operational costs are critical [1, 4].

One of the promising areas in micro-manufacturing is the development of ferrofluid-based transducers [2]. Ferrofluids are colloidal suspensions of magnetic nanoparticles in a carrier liquid, which exhibit liquid-like behaviour under normal conditions but respond dynamically when exposed to magnetic fields [6, 11]. This unique characteristic makes ferrofluids highly adaptable for use in transducers, offering advantages such as precise control, reduced wear and tear compared to mechanical systems, and enhanced efficiency in small-scale applications. The ability to manipulate ferrofluid at micro and nano scales has led to the development of innovative transducers such as solenoid actuators, micropumps, and cantilevers, which are designed to replace traditional mechanical systems [3, 5].

The key advantage of micro-manufactured transducers lies in their versatility and performance enhancement. For example, ferrofluid-based solenoid actuators can replace conventional ferromagnetic cores with a ferrofluid plug, offering smoother operation and reduced energy consumption. Similarly, micro-pumps designed with elastomer membranes and ferrofluids enable more precise fluid control, which is essential in medical and industrial applications [7-9].

This chapter delves into the principles and methodologies involved in the micro-manufacturing of transducers, particularly those using ferrofluids. It explores the fabrication techniques, such as laser cutting and mold-based casting, used to create micro-scale structures. Additionally, the chapter discusses various designs and testing procedures for ferrofluid-based transducers, including solenoid actuators, micropumps, and cantilever-type actuators [10, 12]. The development of these transducers not only demonstrates the capabilities of ferrofluids in micro-manufacturing but also paves the way for more advanced applications in fields such as robotics, medicine, and microfluidics [13, 14].

By focusing on the integration of ferrofluid technology in micro-manufacturing, this chapter highlights the potential for creating efficient, low-cost, and high-performance transducers that can operate in a wide range of environments, further advancing the field of MEMS and smart materials.

## 2. METHODOLOGY

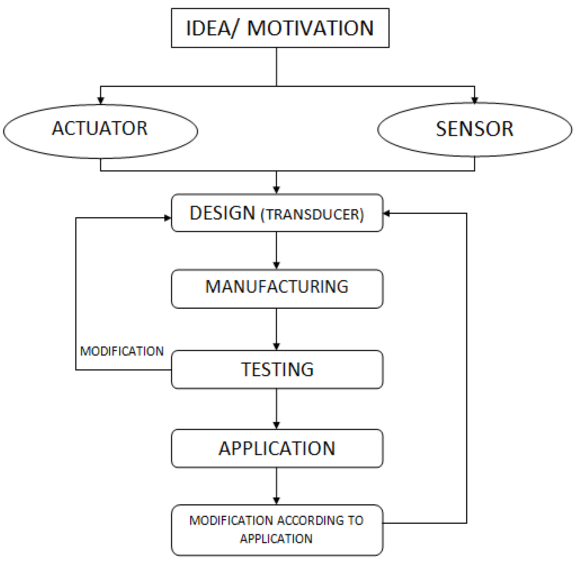



Fig. 1. Flow chart to develop a transducer

The approach for developing a transducer is described in the flow diagram shown in Fig. 1. It starts from an idea or a motivation from any existing structure. A transducer can be developed as an actuator or a sensor, of which function decides the design parameters (input, its processing mechanism, and output). With the completion of the design, the actual fabrication can be done. The next step is to test this manufactured sample for the required performance. If that sample does not offer the required performance, the modification has to be done in the designing step. The tested sample is then applied for different possible problems for solution or possible different applications. In accordance with the application, the transducer sample will be customised in order to meet the need. Over the past decades, researchers and developers have fabricated several microsensors and actuators [3, 14]. These sensors and actuators are converters of energy called transducers. Researchers are starving to build advanced transducers to handle parameters like temperature, pressure, forces, radiation, humidity, and magnetic field. Many of the microsensors and actuators have shown performance exceeding their macroscale counterparts. As ferrofluid has unique properties, it opens up doors to developing transducers based on ferrofluid. Transducers will be fabricated from the micro-fabrication technique, which is called MEMS-Micro Electro Mechanical systems.

## 3. DESIGN OF SOLENOID ACTUATOR

The ferrofluid transducer is based on a solenoid function. The wire carrying currently produces a magnetic field around it, while the Right-hand rule can be the measurement to the direction of the magnetic field. When this wire is turned in a helical coil, it produces a magnetic field, as shown in Fig. 2. The magnetic field is maximum at the centre of the coil. When any ferromagnetic material core is kept inside the coil, it gets pulled into a higher magnetic field. Electric current in a circular loop creates a magnetic field that is more concentrated in the centre of the loop than outside the loop. Stacking multiple loops concentrates the field even more into what is called a solenoid.

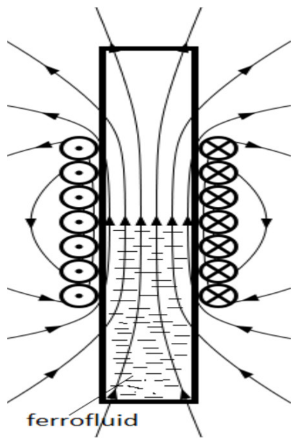



Fig. 2. Solenoid ferrofluid actuator

A wire carrying a current generates a magnetic field whose magnitude and direction at each point in space depend on the length and shape of the wire, the current flowing through the wire, and the location of the point at which the field is determined. A convenient way to depict the pattern of the magnetic field is to draw a line such that each line is always parallel to the magnetic field. The pattern of lines shows the direction of the magnetic field. The magnetic field can be calculated by equation (1):

$$B = \frac{\mu_0 N a^2 I}{2(a^2+Z^2)^{3/2}} \quad (1)$$

## 4. DESIGN OF MICROPUMP

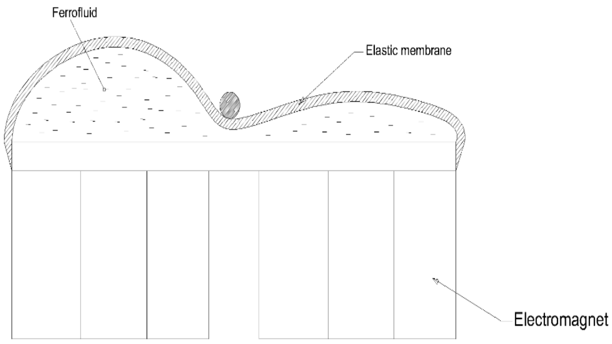



Fig. 3. Micropump using ferrofluid

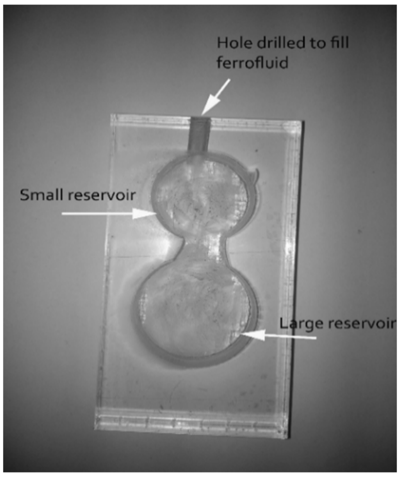



Fig. 4. Micropump body engraved in acrylic material

The idea of a micropump based on ferrofluid is shown in Fig. 3. The two electromagnets are fitted with an elastic membrane at the top. The ferrofluid is placed in the gap between the electromagnet and elastic membrane. The space at the top of each electromagnet acts as a reservoir for the ferrofluid, which one at a time is energised to displace ferrofluid from another reservoir.

Manufacturing of pump body with Laser cutting process. The drawing is drafted on Coral Draw software. The body consists of two sections. Fig. 4 shows the pump body engraved with a laser. These sections will act as a reservoir for the ferrofluid. The different size sections are engraved to get more deflection of the membrane.

### 4.1. Development of cantilever actuator using Ferrogel

The composite is prepared with silicone rubber as a polymer and ferrofluid. A commercially available silicone rubber, also named polydimethylsiloxane, is used to prepare the base polymer. A small strip of composite made from a mixture of silicone rubber and ferrofluid will get attracted to the magnetic field, as shown in Fig. 5. Neodymium magnets are used to create a permanent magnetic field.

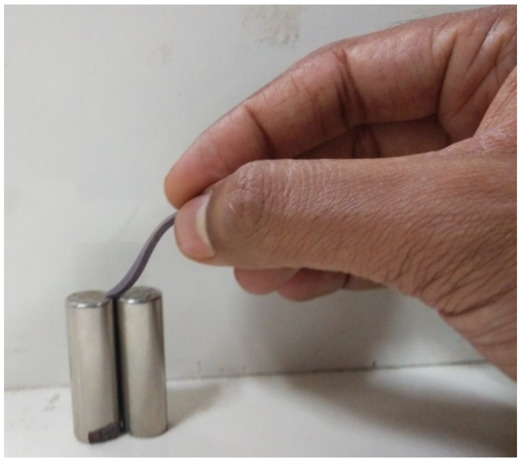
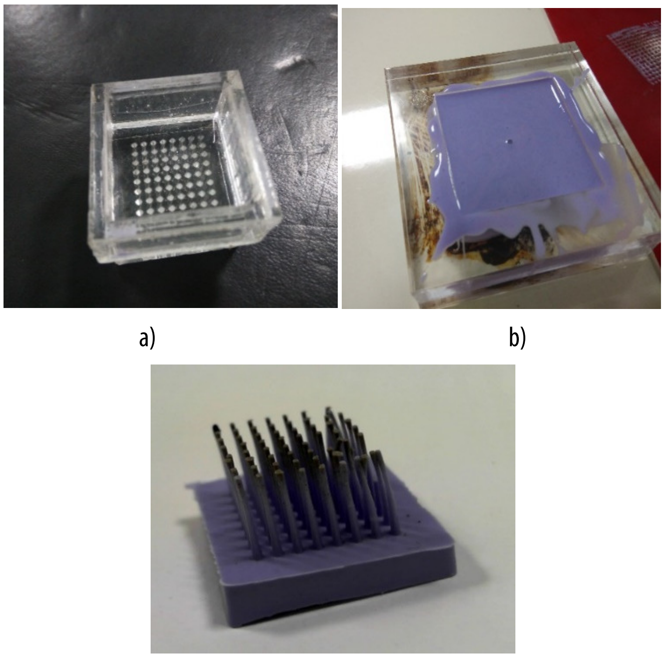


Fig. 5. The Ferrogel cantilever deflected towards a permanent magnet

### 4.2. Mould Making



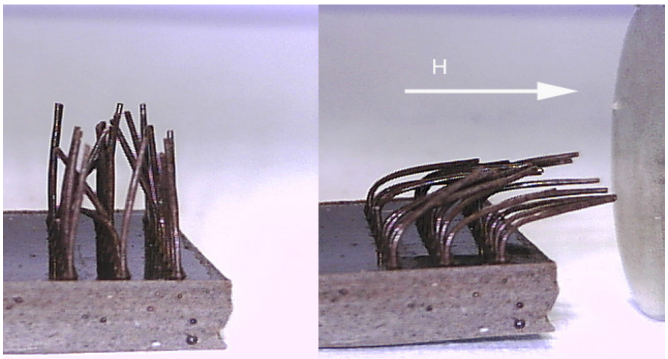
a) b)

c)

Fig. 6. Methylmethyacrylate material used to make mould and PDMS casting

The mould for casting the cantilever is manufactured in methyl methacrylate 10mm sheet shown in Fig. 6(a).

The cavity in the sheet is made by a laser engraver (LaserPro, Spirit) with a laser thickness of 0.001 inch. Fig. 6(b) shows the polymer poured into the mould. An array of cantilever actuators is produced after curing time of PDMS as shown in Fig. 6(c).




a) Composite actuators in absence of a magnetic field

b) Actuators deflected in presence of a magnetic field

Fig. 7. Array of artificial cilia deflected in a magnetic field

Samples with uniform mixing of magnetite particles with PDMS polymer are fabricated as shown in Fig. 7(a). The casted sample looks black in colour because of the presence of magnetite particles and in the absence of a magnetic field. Fig. 7 (b) shows an array of actuators subjected to magnetic field H.

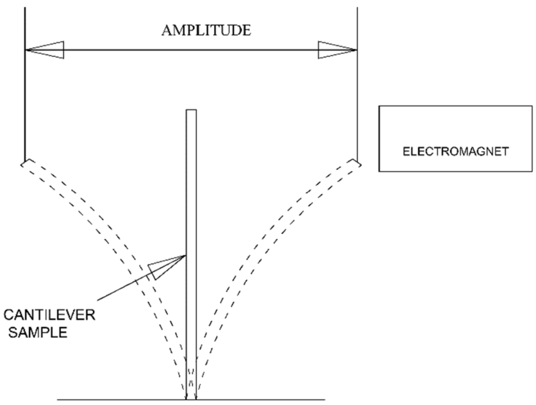
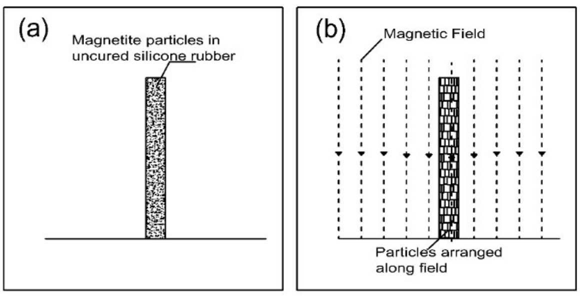



Fig. 8. Actuator measurements

Fig. 8 shows measurement methods used for further analysis. The sample shown in dotted lines is deflected position because of the magnetic field.



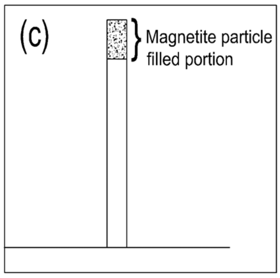




Fig. 9. Schematic of (a) Isotropic, (b) Anisotropic and (c) Tip composite cantilever samples (not to scale)

Different types of cantilevers of same dimensions are fabricated as follows: Isotropic composite with uniform distribution of particles, Anisotropic composite with all particles aligned along one direction,A magnetite particle-loaded tip,

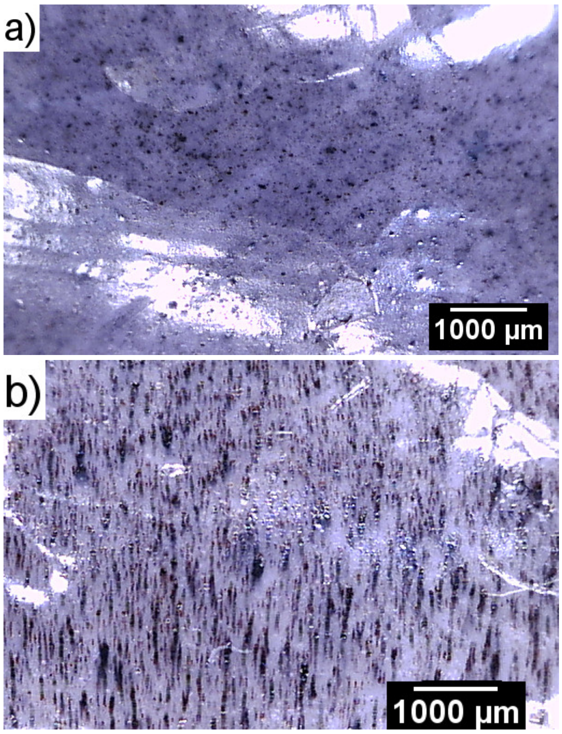



Fig. 10. Microscopic image a) Isotropic sample b) Second of anisotropic sample

As seen in Fig. 9(a), the magnetite particles in the composite are randomly dispersed, giving the composite its isotropic features. The preparation of the second sample involves maintaining the mould in a consistent magnetic field during the curing process shown in Fig. 9(b). This causes the magnetite particles to align themselves along the direction of the magnetic field. The microscopic picture of the composite formed in the absence of a magnetic field and in the presence of one is displayed in Fig. 10 (a) and (b), respectively. To secure the unidirectional arrangement of particles, the mould is held under a consistent magnetic field for seven hours (the polymer's curing period). The process of creating anisotropic composite, which has anisotropic characteristics due to the arrangement of particles along the length of the cantilever, is seen in Fig. 10(b). A third sample with magnetic particles at the tip is created. The cantilever body is composed of silicone rubber, as seen in Fig. 9(c), and a band of magnetite particles fills the tip band located one millimetre from the free end.

### 4.3. Deflection Testing

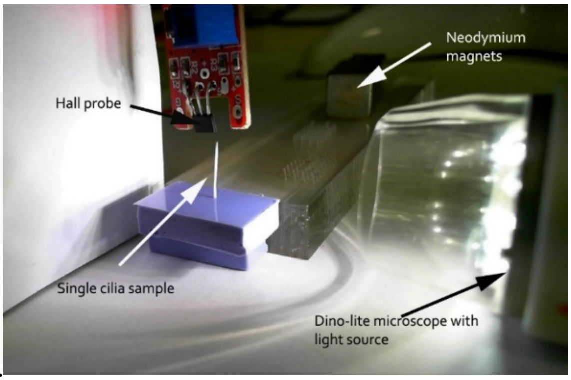
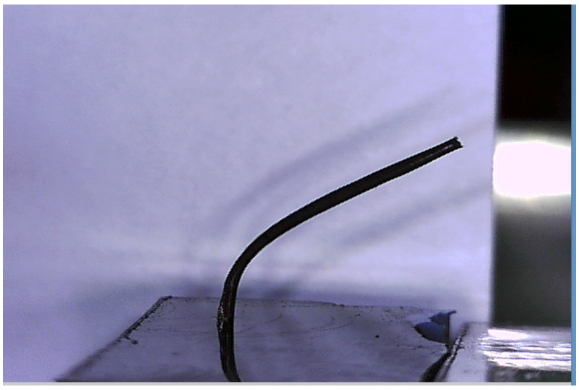
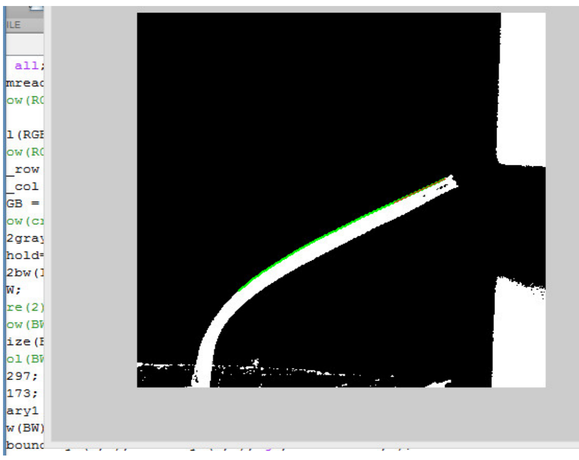



Fig. 11. Experimental setup of the Actuator testing



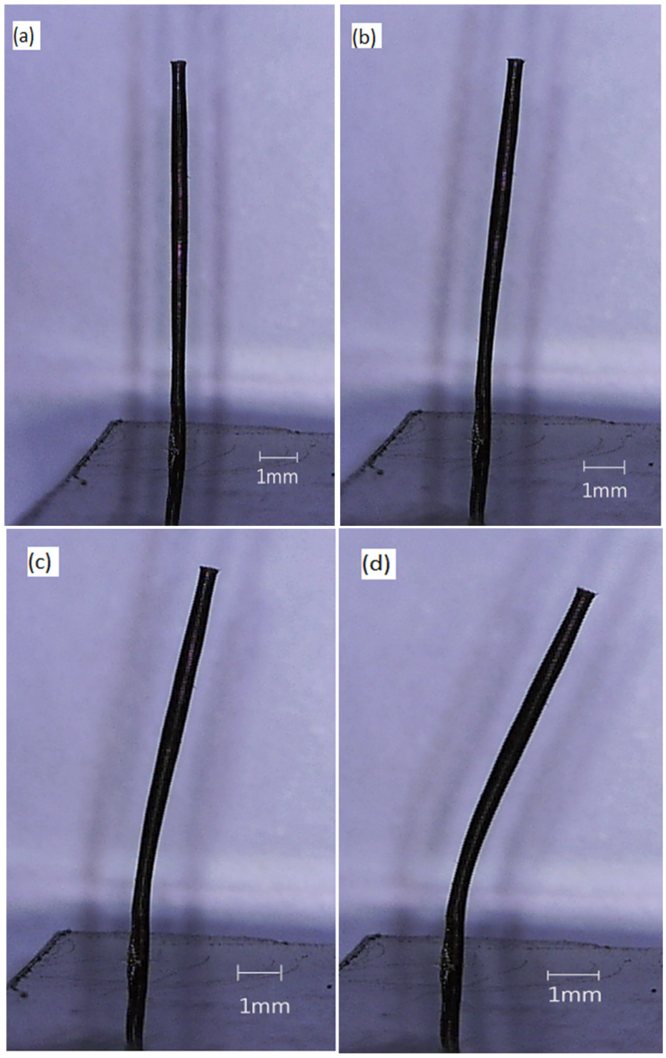
a) RGB Image captured with microscope cantilever beam deflected



b) The captured picture converted into black and white

Fig. 12. Image processing in Matlab

To test a sample's reaction, a single cantilever is exposed to varying magnetic fields, ranging from 0mT to 44T. To generate a magnetic field, neodymium magnets from K&J Magnetics, Inc. in Madison are used. The direction of the magnetic field was perpendicular to the cantilever's length. At the cantilever's tip, a Hall probe is used to measure the magnetic field. Every cantilever sample is maintained in a magnetic field, and a microscope (Dino-Lite digital microscope AM3011) is used to capture the picture. Fig. 11 depicts the experimental setup. MATLAB is used to process microscope deflection pictures (Matlab R2013a). In the Matlab software, new code is compiled to do the following tasks: To measure the deflection angle, the RGB image shown in Fig. 12(a) on the right side is first transformed to greyscale, then converted to black and white shown in Fig. 12(b). The measured angle of the black-and-white image's green edge is visible. Matlab is used to process each image in order to measure the angles.



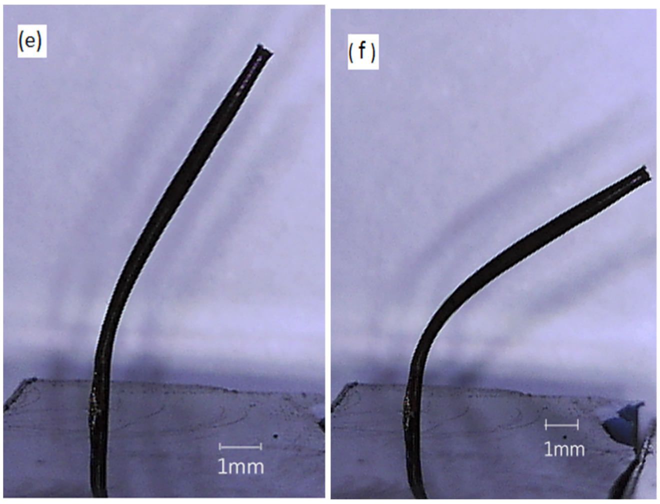



Fig. 13. Movement of isotropic cantilever (400µm dia,10mm length) under a magnetic field

(a) 0mT; (b) 15mT; (c) 23mT; (d) 27mT; (e) 30mT; (f) 36mT

Table 1. Deflection of three samples for different magnetic field

| Magnetic field in (mT) | Deflection of sample (Degree) | | |
|---|---|---|---|
| | Anisotropic sample | Isotropic sample | Tip composite |
| 15 | 1.48 | 3.57 | 0.86 |
| 19 | 4.38 | 6.26 | 1.02 |
| 24 | 47.86 | 11.94 | 2.26 |
| 28 | 68.21 | 22.55 | 3.5 |
| 30 | 71.26 | 33.47 | 4.76 |
| 36 | 78.74 | 62.05 | 8.66 |
| 44 | 82.49 | 74.94 | 22.86 |

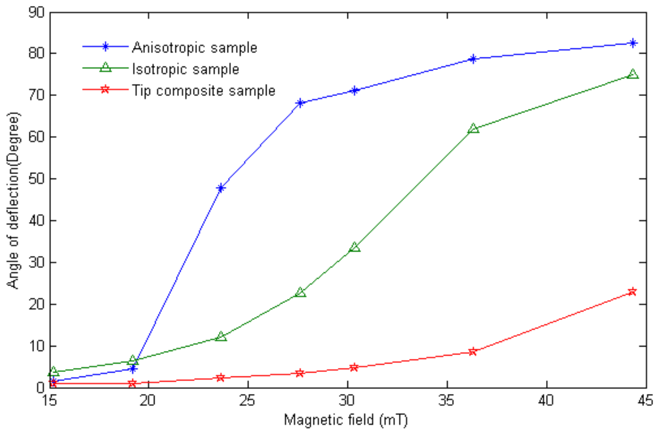



Fig. 14. Bending angle vs magnetic field Comparison of three samples. Dimension of cantilever (400mm dia, 10mm length)

The magnetic field vs. angle of deflection is displayed in Fig. 14. As can be observed, the anisotropic sample exhibits more deflection than the tip composite cantilever and isotropic sample. Fig. 13 illustrates an isotropic cantilever with a particle anchored in a polymer chain. Fig. 13 (a-f) images show the deflection of cantilever for different magnetic field in mili Tesala. In anisotropic samples, these particles attempt to orient in the direction of the applied magnetic field when it is applied in a direction perpendicular to the cantilever's length. The cantilever as a whole is deflected, producing a greater angle, since the magnetite particles are stuck in the polymer. To undo the deflection, apply the field in the opposite direction. A cantilever beam with a consistently distributed load throughout its length is an isotropic cantilever with evenly distributed magnetite particles. When a composite cantilever has a tip-only magnetic field applied to it, the deflection is less than when a cantilever is isotropic or anisotropic. Table 1 gives the deflection angles of all three types of samples for varying magnetic fields. The Isotropic sample shows more degree (3.57) of deflection at a lower magnetic field (15mT) than other samples.

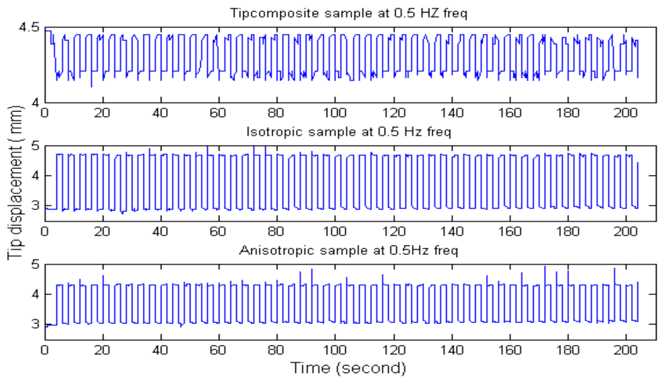



Fig. 15. Oscillation graph for 100 cycles at 0.5Hz frequency of electromagnet (relay on-off)

Dynamic Testing: We continually applied a 33mT magnetic field at a predetermined frequency to study the cantilever's dynamic response. The electromagnetic field provided the excitation frequency. The electromagnet supply was turned on and off using a relay switch (from OCEAN controls). The magnetic field was measured using a fixed Hall probe. The displacement of all three types of composite can be observed in Fig. 15.

It is evident from the mentioned facts above that an isotropic sample exhibits a greater amplitude at the same frequency and magnetic field. Silicone rubber makes up the body of the tip composite sample with a lesser amplitude. The isotropic cantilever exhibits a reduced rigidity compared to the silicone body tip composite due to the randomly dispersed magnetite particles. The magnetite particle trapped in the silicone rubber is the cause of the change in stiffness.

## 5. CONCLUSION

Gels that respond to magnetism are successfully made. Actuators in many forms may be made using these gels. We presented a low-cost, straightforward manufacturing process for these micro-level cantilevers. These cantilevers have use as both sensors and actuators. Tests on cantilevers were conducted under various magnetic fields. As isotropic, tip composite, and anisotriptic samples, three distinct samples were examined. 82° deflection for 44 miliTesla was the best response (the anisotropic sample outperformed the other isotropic and tip composite). Three samples' dynamic responses were compared at various frequencies. The amplitude of an isotropic and isotropic sample is higher than that of a tip composite. Moulds made of methyl methacrylate material were used to create cantilevers with sizes ranging from several millimetres to 200 microns. Laser engraving provides an efficient and cost-effective way to make these moulds. These cantilevers work best as micro pumps, micro valves, and artificial cilia. The second transducer solenoid actuator was tested for two tube diameters as 1.75mm capillary and 10.10mm glass tube. The solenoid actuator gives the ferrofluid movement up to the center of the coil. It is observed that solenoid actuators based on ferrofluid can be used for low-load applications. Actual-load carrying capacity can be calculated with a special instrument. It is been proven that ferrofluid shows good heat transfer. The use of ferrofluid in solenoid can resolve the problem of self-heating of solenoid.

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