Design and Simulation of Scanner Wrapped by Flexible Microcoil Embedded in Polymer Film for Single-Optical Endoscope Application

Mengyuan Zhao¹, Zhuoqing Yang¹, Xiaojian Xiang¹, Bin Sun², Guifu Ding¹ and Xiaolin Zhao¹

¹National Key Laboratory of Science and Technology on Micro/Nano Fabrication, Shanghai Jiao Tong University, No.800 Dongchuan Road, Shanghai 200240, CHINA
²Institute of Biomedical and Health Engineering, Shenzhen Institute of Advanced Technology, Chinese Academy of Science, Shenzhen, 518055, CHINA

E-mail: zhaomy@sjtu.edu.cn, yzhuoqing@sjtu.edu.cn

Abstract. A single optic fiber scanner with large scanning angle, based on novel electromagnetic driven, is presented. The cylinder magnet and weight are fixed on the fiber, and vibrate under its second-order frequency by driving racetrack coils on the tube. The flexible driving coil is fabricated by uncomplicated planar MEMS technology on polyimide film, and wrapped on the tube. The electromagnetic and mechanical properties of the endoscope system are studied. Experimental results show that the maximum of the second resonant scanning angle is 9.47°.

1. Introduction
There are two categories of image acquisition of human internal organs and ducts without damaging human body, one is structure-based medical image acquisition, like computed tomography (CT).[1, 2] The CT machine generates tomographic image of the structure of the scanned tissue by using rays or ultrasonic wave, but it provides the image with low spatiotemporal resolution (millimeters, seconds); another is surface-based medical endoscopic technology with high spatiotemporal resolution (micrometers, milliseconds), the medical endoscope captures the imaging by visualizing the surface of tissue and organ of internal human body directly. Thus, the medical endoscopic technology can easily detect pathological changes of tissue and organ. The range of application for internal organs is obviously decided by the flexibility and diameter of medical endoscope, in addition, a fine and flexible endoscope can effectively reduce pain sensation and tissue trauma.[3]

There are two kinds of endoscopes in the modern medical application area, fiber bundle endoscope and image sensor endoscope. The diameter of image sensor endoscope is limited by the size of sensor (CMOS and CCD), the small size of imaging sensor will reduce imaging quality, miniaturization is extremely difficult on the premise of keeping high resolution. The fiberscope can be miniaturized by reducing the number of fiber in the tube, but it also will impact the imaging quality. To get the high resolution and smaller size, a new fiber endoscope with a rapid scanning fiber has been researched, the endoscope with a single fiber can be divided into electromagnetic and piezoelectric type depending on different driving mode. The research of piezoelectric driven fiber scanner is more mature, the theory of
scanning is that PZT actuators drive fiber vibration under alternating current with a certain frequency,[4] but the applied high voltage and toxicity of PZT material are not suitable as medical endoscope. The fiber optic scanner with electromagnetic driven has much advantage that piezoelectric driven lacks, like low power, low toxicity. The electromagnetic actuator fiber scope consist of the driven part of generating driving magnetic field, like electromagnetic coil or permanent magnet, and a vibration part, it contains a fiber and the device that is fixed on the fiber and interacts with magnetic field. Some researchers use 3D MEMS process to fabricate a tilt coil as a driven part on the tube surface,[5] but it does not provide a large force output, beyond that, the manufacture is complex and expensive. Therefore we need a new design with easy processing and good driven method for providing a large device.

In this paper we report an electromagnetic single fiber endoscope with wrapped driven flexible coil, the fiber scanner is based on an optical fiber with magnet. The electromagnetic feature of the microcoil was simulated in order to theoretically analyze the interaction between magnet and coil, and the dynamic property of fiber vibration system was calculated and simulated. The device was made and properties were characterized dynamically.

2. Design and characters analysis

2.1. Design of the fiber scanner system

The design can be seen from figure 1(a), the scanning fiber system is composed of fiber weight and magnet, the shape of magnet and weight is cylinder with a round hole, and the fiber move through the hole of them and fixed by UV curing glue, the magnet and mass are placed on the middle and front part of the fiber, respectively. The fiber system is placed at the longitudinal axis of a polyimide tube. The driven device is a flexible circle microcoil that be wrapped on the outside surface of the tube. The driven coil is fabricated on flexible polyimide film, then, it is wrapped on the tube. Two of the same helix coils that are symmetrically wrapped on the surface of the polyimide tube can provide applied magnetic field for magnet. Its outer and inner diameters are 2.0mm and 1.8mm, which is fabricated and embedded in a flexible polyimide film, as shown in figure 1(b). The soft material CoNi as the magnet, because of low coercive field strength, the soft magnet is easy to be magnetized by along axis, and change the direction of magnetization by external field and when the driven coil is applied a periodic voltage, the magnet will generate a magnetized torque and impel the fiber to vibrate with the same frequency as external current. When the fiber system vibrates on its own resonant frequency, the fiber will resonate and a remarkable scan procedure can be obtained. In addition, the weight can change the resonant mode of the scanning system and can increase the resonant amplitude at high-order resonant modal; the fiber scope will achieve the goal of large scanning angle in the narrow space.

Figure 1. (a) 3D sketch of the fiber optic scanner; (b) 3D stretch of the drive coil and tube; (c) 3D model of the wrapped coil.
2.2. Electromagnetic properties analysis

Electromagnetic characters of the wrapped microcoil are the important for the fiber endoscope, in order to analyze these, finite element emulation software COMSOL Multiphysics was used. The model of curved coil has been built in the Solidworks, and is import in COMSOL Multiphysics, as shown in figure 1(c). The geometry parameter is 8 of turns, 50 of line width and pitch, and the maximum outside diameter is 3mm; the input current is 0.1A. The generating magnetic field simulation of the drive coil as shown in figure 2(a). The magnetic field is symmetric about the central axis of the coil. The magnetic field is closer to the microcoil and the strength is stronger, and only a little area can keep the relatively higher magnetic field strength. Therefore, to increase the area of high magnetic field, a coil with track type is simulation, as shown in the figure 2(b), the straightway is 2mm and the current is 0.1A. the simulation shows that the magnetic field with the same direction occurs in the straight-line area, and the magnetic field strength is high enough.

![Figure 2](image2.png)

**Figure 2.** The simulation of the magnetic field distribution: (a) circle coil; (b) track coil.

![Figure 3](image3.png)

**Figure 3.** Schematic of torque T calculation.

In order to get a larger driven force, the theory of magnetized soft magnet should be studied, to simplify the analysis, a CoNi cylinder is placed inside a uniform magnetic field that is perpendicular to the axis of magnet as shown in figure 3. The soft magnet generates a torque $T_H$, it can be expressed as[6]:

$$T_H = V \times (M \times H_{ext}) = VMH_{ext} \sin \theta$$  \hspace{1cm} (1)

Where $V$ is the volume of the magnet, $H$ is the magnetic field and $M$ is the magnetization vector, and the angle $\theta$ is between $M$ and $H$. The magnetization vector of the soft magnet varies with the
changes external magnetic field along the direction of magnetization vector: \( H_a = H_{ext} \cos \theta \). When the magnet starts to be magnetized by \( H_{ext} \), a demagnetizing field \( H_d \) will be generated inside the magnet: \( H_d = -N_M M / \mu_0 \), where \( N_M \) is the shape-anisotropy coefficient and \( \mu_0 \) is the permeability of vacuum; and the \( H_d \) is equal to the \( H_s \) at the steady state. The maximum is the saturated magnetization \( M_s \). Taken together, the value of magnetization vector can be expressed as:

\[
M = \left( \frac{\mu_0 H_{ext} \cos \theta}{N_M}, M_s \right)
\]

When \( M \) rotates away the easy axis, a magnetic-anisotropy torque \( T_a \) is generated to stop the rotation of the magnetization vector:

\[
T_a = -K_a \sin 2\omega
\]

Where \( K_a \) is magnetic anisotropy constant, and \( \omega \) is the angle between the easy axis and \( M \). A opposite torque \( -T_a \) will be exerted on the magnet, and drive the magnet (the easy axis) to coincide with the magnetization vector.

2.3. Dynamic Response Analysis

We use the simulation software COMSOL to evaluate the dynamic properties of the fiber system, the system has its own multi-stage resonant frequencies, and corresponding different resonant modes, figure 4 (a) shows the first two order resonant mode shape, and resonant mode shape of the fiber vibration system. In the first order resonant mode, weight and magnet arrive their amplitude with same phase at same time, and the second order resonant mode is opposite phase under the same condition. The harmonic analysis is used to calculate the displacement amplitude of each resonant mode in figure 5, the harmonic force is 5e-6N, and excitation frequency is set from 10Hz to 200Hz. The results indicates the displacement amplitude of the first model is much more than the second model, and the displacement will increase with increasing the harmonic force. But the inner space of the tube has been limited, and the maximal resonant amplitude of the fiber scanner system is the inner diameter of the tube.

![Figure 4](image)

**Figure 4.** (a) the simulation of the first two order resonant mode; (b) the corresponding scanning angle in the tube.

When the tip of fiber touches the inner wall with different driven force under the first and second resonant frequency, the system has the same maximum vibration amplitude respectively, as shown in figure 4 (b). Compared with the vibration under the first order resonant frequency, the vertex of the scanning angle is more adjacent to the head of scanner tube, which is the static point between weight and magnet, and it can provide a larger visual field.

\[
\begin{align*}
IOP \text{ Conf. Series: Journal of Physics: Conf. Series 986} \ (2018) \ 012035 \quad \text{doi:} 10.1088/1742-6596/986/1/012035
\end{align*}
\]
Figure 5. The simulation of the displacement amplitude of the fiber tip from 10Hz to 200Hz.

3. Fabrication and Measurement
The manufacture of coil is important to the fiber endoscope, the driven microcoil should be soft enough to be wrapped on the tube, and be easy to fabricate by the traditional MEMS planar manufacture technology. The polyimide film is used as flexible substrates because of its stability and compatibility in fabrication[7]. The coil is fabricated on the polyimide film that has been fixed on the planar substrate by traditional MEMS planar fabrication process, and to protect the coil, the processed coil is encapsulated by the solidified polyimide. Figure 6 shows the fabrication process of the coil and the optical image.

Figure 6. The main fabrication process of the driven microcoil and the photo of the wrapped coil.

To measure the scanning angle of the fiber scanner that was discussed in previous section. The measurement system is built as shown in figure 7. The driven alternating current is generated by the function generator and current amplifier, and the vibration situation of fiber vibration system can be observed by optic camera. Figure 8 shows the photograph of the first two order frequency 24Hz and 157Hz. weight and magnet have the same phase at the first order frequency, and arrive the maximum at the same time. but they have the opposite phase under the second order frequency, the fiber has a large bending deformation and has larger scanning angle. The measured maximum scanning angle of the first two resonant frequency is 2.98° and 9.47°.
4. Conclusions
This paper presents a design of a fiber-optical endoscope with electromagnetic driving flexible microcoil, the electromagnetic and dynamic property has been discussed and simulated, the driving coil is fabricated on the polyimide film by planar MEMS process. The fiber scanner system vibrates at its own the second order resonant frequency can provide a larger scanning angle, and the scanning angle is 9.47° by optical camera.

5. References
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