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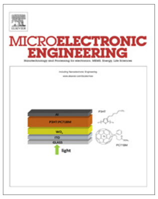

Segmented magnetic circuit simulation of the large displacement planar micro-coil actuator with enclosed magnetic yokes

Xiaodan Miao [a,*], Xuhan Dai [b], Yi Huang [b], Guifu Ding [b], Xiaolin Zhao [b]

[a] *College of Mechanical Engineering, Shanghai University of Engineering Science, Shanghai 201620, China*
[b] *Science and Technology on Nano/Micro Fabrication Technology, Research Institute of Micro/Nano Science and Technology, Shanghai Jiao Tong University, Shanghai 200240, China*

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ABSTRACT

This paper proposed the segmented magnetic circuit method to simulate the large displacement planar micro-coil (PMC) microactuator for micro-magnetic relay applications, which adopted enclosed miniaturized magnetic yokes. The segmented magnetic circuit model has been established to describe the magnetic flux variation and the redistribution effects of the magneto motive force (MMF) induced by the large air gap and large ratio between the radical and vertical size. Based on the optimized parameters, the PMC microactuator was fabricated through UV-LIGA technology and tested to verify the model under scrutiny. The large displacement was realized by using laminated photoresist sacrificial layer process. After comparing the measurement and simulation results, it is concluded that the modified model can describe the influence of key parameters over the output electromagnetic force. The proposed methodology is demonstrated to be efficient in the analysis and optimization of the magnetic MEMS devices of PMC structures with embedded magnetic yoke.

1. Introduction

Magnetic micro-actuators (MMAs) have emerged as a useful component for many applications in MEMS including microfluidics, micro-optics, particularly for MEMS switches [1–3]. MMA is attractive because of its non-contact nature [4] as well as other advantages such as high output force, large working distance, low actuation voltage and fast response [5–8] compared with other microactuators [9–11]. Microrelay is one of the typical examples of those applications.

MMA works mainly based on the interaction between the magnetic materials and the active (coils) or passive magnetic field sources (permanent magnets) [12,13]. Micro-coil is the key component of the MMA. The traditional coil configurations, such as the solenoid micro-coil, are a complex three-dimensional structure [5,7,15], It is difficult to be implemented with batch fabrication technologies because the micro-fabrication is basically a two-dimensional process. In order to solve this problem, the micro planar coils (PMC) with different configurations were proposed. The configurations included meander micro-coil [14], planar spiral micro-coil [16,18], etc, which demonstrated the possibility for batch fabrication and size reduction. Another key element of the magnetic microactuator is the displacement. Compared with the traditional magnetic relay, the displacement was reduced as well as the volume. In order to acquire large displacement as well as isolation, the permalloy was adopted into the microcoil as magnetic yoke to improve the efficiency of the magnetic yoke. Ren et al. [5] adopted the magnetic yoke in the 3D spiral microcoil, and the displacement reached 100 μm. However, the 3D spiral microcoil is not easy for batch fabrication. Hartley et al. [6] developed a large displacement magnetic microactuator for RF MEMS. The potcore has a footprint of 0.8 mm^2 and for a driving current of 1.4 A (corresponding to a power dissipation of about 80 mW) which generated an initial force of 0.11 mN which is sufficient to close a 100 μm gap. However, the big driving current leads to high power dissipation at closing state. Therefore, displacement of the previous microactuators is less than 100 μm, which was limited by the fabrication process and magnetic circuit design.

In addition, different modeling methods for these PMC configurations were proposed. Based on the Finite Element Method (ANSYS software), Ko and co-workers [16] analyzed the influence of the dimensions of the core and the magnetic material block on the performance of a PMC actuator. However, a direct and in-depth description of the influence of different parameters cannot be obtained in FEM, let alone its calculation intensive and time consuming feature. Feustel et al. [17] and Beyzavi and Nguyen [18] calculated the magnetic field of the PMC based on Biot-Savart's Law. No magnetic yoke

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* Corresponding author.
E-mail address: mxd8868@hotmail.com (X. Miao).

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was adopted in the PMC under consideration. In previous simulation, the Biot-Savart's Law can only be adopted for PMC without magnetic yoke. The magnetic circuit method is a well developed tool for quick analysis of the macroscopic magnetic circuit. In the microscale, because of large ratio between the vertical and horizontal size of the PMC with large displacement, the magnetic flux variation and the redistribution effects of the magneto motive force (MMF) may have important effect on the output characteristics. However, it was ignored in the present magnetic circuit method.

Based on the problem mentioned above, this paper proposes a PMC microactuator with larger displacement (390 μm) than previous work. In order to improve the magnetic field efficient, the enclosed magnetic yokes located at the center, edge and bottom the coil respectively, which could reduce the magnetic reluctance and concentrate the magnetic flux. Above all, this paper developed an improved analytical model based on the section magnetic circuit to accommodate the characteristics of the proposed configuration. A two-step characterization process was composed to validate the model. It is demonstrated to be an efficient tool for optimization of the device key magnetic parameters.

2. Structure and simulation of the microactuator

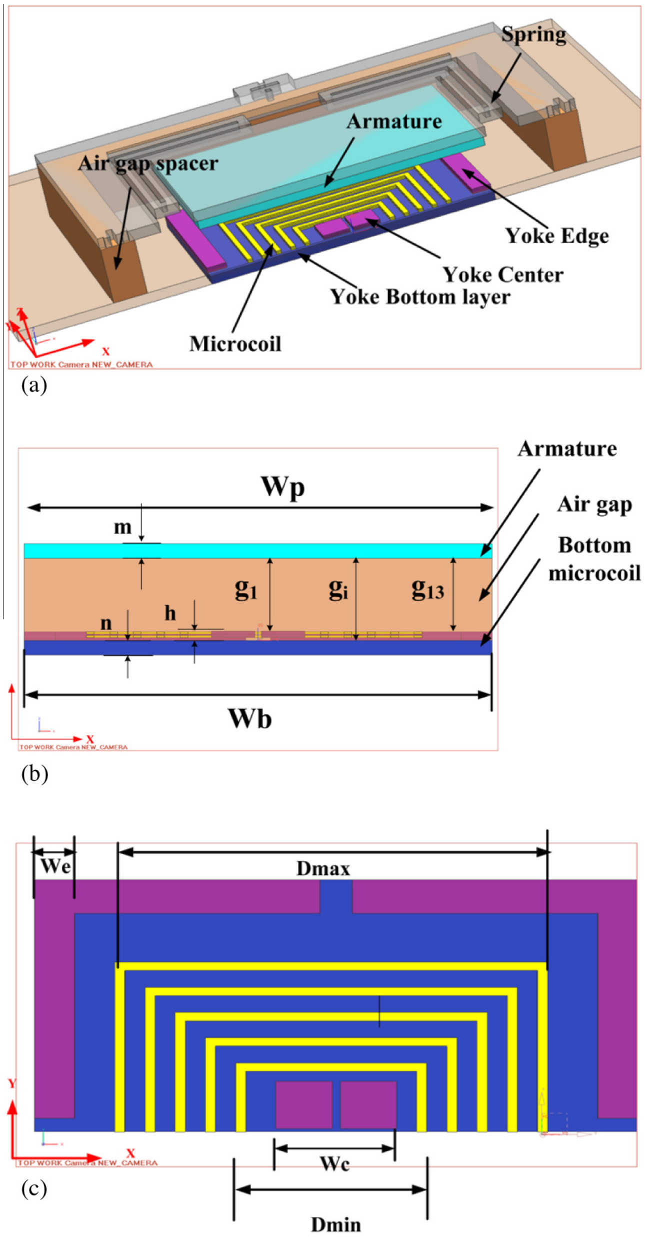
The typical configuration of a PMC microactuator with enclosed magnetic yoke is shown in Fig. 1 and Table 1. The two main components of the device are a microcoil with enclosed magnetic yoke and a spring with the armature as shown in Fig. 1(a). The bottom microcoil is consisted of a copper planar microcoil with permalloy magnetic yoke in the center, bottom and edge position as shown in Fig. 1(c). The top spring is consisted of a permalloy platform connected with four nickel frog leg type beams fixed by the supporters as shown in Fig. 1(a). The air gap between the bottom microcoil and top spring is formed by the supporters as shown in Fig. 1(b). The output displacement of the microactuator depends on the balance between the spring elastic force and the electromagnetic force generated in the coil. By controlling the current inside the coil, the electromagnetic force and thus the output displacement could be adjusted. Since the force is determined by the magnetic flux flowing through the gap between the armature and microcoil, a quick and accurate analysis of the magnetic circuit is necessary.

Firstly, in this proposed concept, the radial length of the magnetic core (3000 μm) is far larger than the vertical thickness (10 μm) as well as the air gap length (390 μm). As a result, the magnetic resistance of the air gap is large, which reduced the major magnetic flux and increased the magnetic flux leakage along the radial direction. As a result, the magnetic flux will not only flows primarily through the gap at the yoke surface, which is indicated as the path of principal magnetic flux (Solid line in Fig. 2), but also through gaps along the radial positions. These fluxes are marked with red dashed lines in Fig. 2.

Secondly, for macro actuator, the traditional solenoid is winding around the bottom magnetic core. Therefore, the MMF is considered as lumped one in the magnetic circuit model. But, in this proposed configuration, the planar spiral microcoil with different radius is winding around the center magnetic core. Thus, the MMF corresponding to annular part of the microcoil along the radial direction of the magnetic circuit is different.

As a result, the model of this proposed configuration should consider both the magnetic flux leakage between the center and edge magnetic core as marked in Fig. 2 and its distribution effect of the MMF along the radial direction.

2.1. Magnetic circuit modeling



(a)

(b)

(c)

Fig. 1. (a) The schematic diagram of a PMC microactuator. (b) Cross-section of the PMC microactuator. (c) Top view of the PMC.

Table 1
Structure parameters of the planar microcoil with enclosed magnetic yoke.

Parameters	Symbol	Value (μm)
Side length of the armature	Wp	3000
Side length of the yoke bottom layer	Wb	3000
Thickness of the armature	m	10
Thickness of the yoke bottom layer	n	10
Width of the yoke edge	We	200
Height of the yoke center	h	50
Width of the yoke center	Wc	600
Gap at the yoke center and edge	g_1, g_{13}	390
Gap at other radial positions between the yoke center and edge	g_2–g_{12}	340
Side length of the outermost turn of the coil	D_{max}	2800
Side length of the innermost turn of the coil	D_{min}	760

Considering the difference mentioned above, such as the magnetic flux leakage, distribution effect of MMF, etc, the magnetic circuit of the PMC microactuator was modeled, as shown in Fig. 3. The magnetic circuit was divided into 10 parts preliminary along radial direction and annular part of the magnetic core and