Dynamic Modeling of Magnetic Film Actuators

Serhan O. Isikman, Hakan Urey
Koç University, College of Engineering, Istanbul, TURKEY
Tel +90-212-338-1474, Fax +90-212-338-1548, E-mail: hurey@ku.edu.tr

Abstract—**Dynamic behavior of magnetic film based actuators is modeled and the model is validated with experiments. An external electro-coil is used to actuate the cantilever scanners, which has an electroplated 30 um thick permalloy layer. Resonant vibration of the actuator is modeled accurately without constraining the external field to be uniform or the ferromagnetic material to be saturated.**

Index Terms: **magnetic actuators, dynamic, vibration, permalloy, scanners**

1. INTRODUCTION

This paper introduces a magnetic model for calculating the dynamic deflections for permanent magnet and soft magnetic film actuators and extends the previous work by the authors, which was limited to static deflections. Thin film electromagnetic actuators are widely used in applications like optical communications, display, imaging, sensing and relay switching. The magnetostatic force and torque models are explored in detail for cases where the soft magnetic material is saturated [1] and where the external field is assumed to be uniform and perpendicular to the magnetic film magnetization direction [2]. In [3], a model was developed for static actuation without limiting the external magnetic field to be uniform or the ferromagnetic material to be saturated. For applications where the magnetic actuator is vibrated by a time varying external field, a dynamic model is required to characterize the deflection of the device. Although the device under study has dimensions in the order of millimeters, the model is scalable and perfectly applicable for magnetic micro-actuators.

2. STRUCTURE AND OPERATION

Fig. 1 illustrates the device investigated in this work, which is a cantilever beam with a magnetic permalloy film plated on the paddle at the free-end of the cantilever.

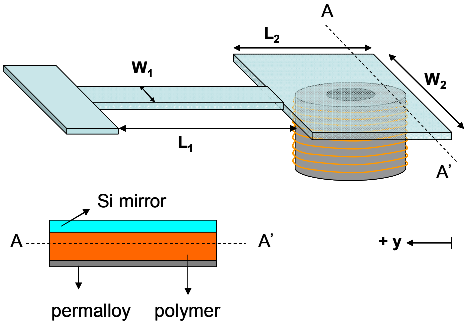

Fig. 1. Schematic of magnetic actuated cantilever scanner. Permalloy plated paddle area is 8mm x 8mm with a silicon mirror mounted on top for optical scanning. Cross section along AA' shows the material layers.

The external electro-coil is driven with an AC signal. The field produced by the coil magnetizes the permalloy film and generates a net torque and force vibrating the whole cantilever structure in the out-of-plane bending mode at 82.6 Hz resonance frequency.

3. DYNAMIC ACTUATION MODEL

Dynamic actuation is modeled using a distributed non-uniform force and torque across the soft magnetic film, which can be translated to find a net force and torque at the tip of the cantilever assuming the mirror piece is rigid. Since there is both a net torque and force in the system, the governing equations can be written as follows:

$$J\ddot{\theta} + b_T\dot{\theta} + k_\theta\theta = T(\theta) \tag{1}$$

$$M\ddot{x} + b_F\dot{x} + kx = F(x) \tag{2}$$

In the above equations J, b_T and k_θ are the mass moment of inertia, damping, and angular spring constant; M, b_F, and k are the mass, damping, and linear spring constant of the system respectively. J, k_θ, M and k were calculated using Euler-Lagrange's energy methods. Damping coefficients b_T and b_F were calculated using the measured quality factors of the resonant structure.

Force and torque calculations are performed similar to the magnetostatic case using the equations below [3]. It is important to note that M and H are time-dependent for the dynamic case. Fig. 3 depicts the distributed force and torque calculation pictorially. Magnetic field data to use in numerical calculations is obtained from FEM simulations.

$$\begin{aligned} F_{N-1} &= M_{N-1}\cdot W_2\cdot t_2\cdot H_{N-1} \\ F_N^{'} &= M_N\cdot W_2\cdot t_2\cdot H_N \end{aligned} \tag{3}$$

$$\begin{aligned} T_{N-1} &= (F_{N-1}^{'} - F_{N-1})(N-2)\Delta L\cos\theta \\ T_N &= F_N(N-1)\Delta L\cos\theta \end{aligned} \tag{4}$$

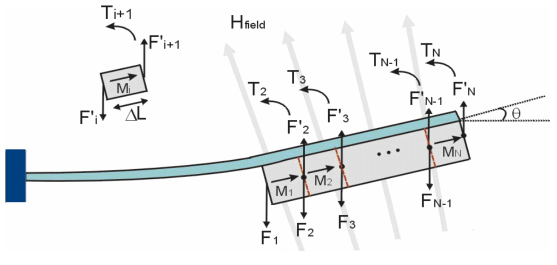

Fig.3. Distributed force and torque exerted on magnetic material. The inset shows the case for a single unit magnetic element.

Due to the large deflections of the cantilever, magnetic field experienced by the permalloy film varies with the position. Hence, the torque and the force need to be calculated as functions of displacement. Therefore, (1) and (2) need to be solved numerically. In order to find the total

1-4244-0925-X/07/$25.00 ©2007 IEEE

deflection of the cantilever tip, x_{total}, independent solutions of the two equations of motion have to be superposed as follows:

$$x_{total}(t) = x(t) + 0.5 \cdot L_1 \cdot \theta(t) \tag{5}$$

where the second term in the addition is the linear displacement corresponding to an angular displacement $\theta(t)$ given by [4].

In order to validate our model, two types of dynamic actuation configurations are modeled as discussed below.

A. PERMANENT MAGNET ACTUATION MODEL

In this scheme, instead of the permalloy film, a permanent magnet with magnetization of M = 0.55T is attached on one side of the scanner and the structure is actuated by an external electro-coil. Since magnetization is constant, torque and force, being functions of MH product, are linearly proportional to the perpendicular component of the magnetic field of the coil. Therefore, both the excitation current and the vibration are at the mechanical resonance of the device. In numerical calculations of torque and force, permanent magnet attached to the scanner is divided into elements, which have the same magnetization but different external magnetic fields. Fig. 4 shows the experimental and theoretical deflection curves as a function of the position of the scanner over the coil, with negative position being toward -y direction as shown in Fig. 1. The separate curves for deflection due to the force and the torque are also provided to demonstrate the significance of modeling force and torque separately, and superposing the corresponding deflections. Note that the net force and torque are in opposite directions for y < 0 and in the same direction for y>0.

B. SOFT MAGNETIC FILM ACTUATION MODEL

In this configuration, cantilever beam is actuated with an electroplated permalloy layer, which is a NiFe composite with high permeability. The large length-to-thickness ratio of the permalloy film results in a dominant shape anisotropy. Hence, magnetization remains always in-plane, with different local magnitudes and orientations at each point of the magnetic material due to spatially varying magnetic field of the coil. Therefore, as was demonstrated in [3] for static deflection cases, the permalloy structure can be modeled as an array of permanent magnets with different magnetizations. In order to calculate the torque and the force, the permalloy film is divided into uniform volumetric elements where the magnetization of each element is calculated using a linear M-H relationship with μ_r = 150 and M_{sat} = 0.75 (i.e., hysteresis effects are not modeled). Since large resonant deflections can be achieved at fairly low magnetic fields, the permalloy film does not reach saturation; hence, the net force and torque are proportional to the square of the applied current. In this configuration, the magnetization direction and amplitude vary across the magnetic film. Therefore, exciting the system at half its mechanical resonance frequency results in resonant vibration of the device. Fig. 5 shows the experimental and theoretical deflection results as a function of scanner position. Separate plots of force and torque are also included to point out that their superposition yields the accurate deflection model. In this actuation mechanism, force and torque were found to have opposing directions for y in the range 0<y<4 and for y<-5, resulting in subtraction of the force and the torque contributions.

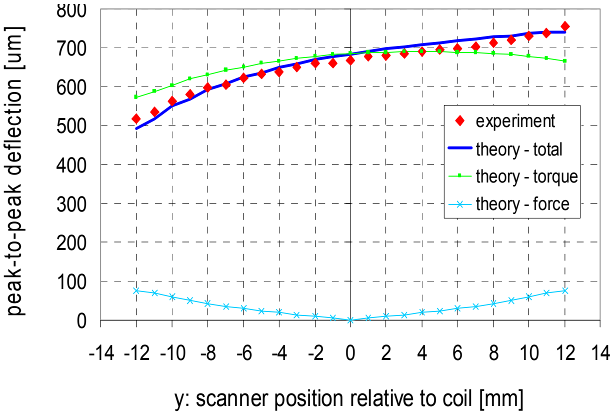

Fig.4. Permanent magnet actuated resonant cantilever deflection as a function of scanner position wrt coil, which is driven by a 2.5 mA rms current. Measured Q factor is 33.

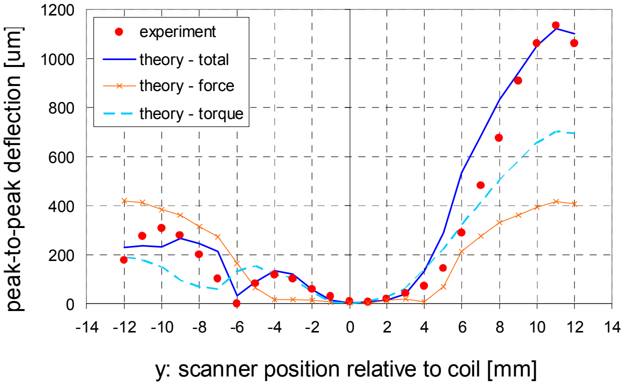

Fig.5. Permalloy film actuated resonant cantilever deflection as a function of scanner position wrt coil, which is driven by a 40 mA rms current. Measured Q factor is 80.

In summary, dynamic deflection of magnetic film actuators is modeled without assuming uniform external field or saturation in the magnetic material. The hysteresis effects are not included in the model yet the agreement between the model and the experiments are quite good. Note that the model given here is valid when the magnetic film is thin (i.e., length to thickness ratio is >>1) and the shape anisotropy is dominant. Even though the structures tested are of mm size, the model is applicable to MEMS scanners and actuators.

REFERENCES

[1] J.W. Judy, et. al, “Magnetic microactuation of polysilicon flexure structures”, *J. of MEMS*, vol.4, pp. 162-169, 1995

[2] C. Liu, Y.W. Yi, “Micromachined magnetic actuators using electroplated Permalloy”, *IEEE Trans. on Magn.*, vol.35, pp.1976-1985, 1999

[3] S.O. Isikman, O. Ergeneman, A.D. Yalcinkaya and H. Urey, “Modeling and Characterization of Soft Magnetic Film Actuated 2-D Scanners”, *IEEE J. Sel. Top. Quant. Elec.*, vol. 12, pp. 283-289, 2007.

[4] W. C. Young, R.G. Budynas, “Roark's formulas for stress and strain”, 7th ed., New York, McGraw Hill., 2002.