INTEGRATED MAGNETICALLY ACTUATED MICRORELAY

Anca TOMESCU, Sorin ANTONIU, Gabriela CIUPRINA
Electrical Engineering Dept., POLITEHNICA University – Bucharest
Stefan COLLER
S.C. COL–AIR S.R.L. Bucharest

The mechanic characteristic of an integrated magnetically actuated microrelay is calculated by an approximate analytical method and a finite element numerical method.

INTRODUCTION

Microdevices and micromotors are a subject of increasing interest due to their multiple applications in industry, medicine, military, and many other fields. Integrated circuit technology is used in the manufacture process of microdevices, which are thus subjected to associated restrictions. In particular, deposition of layers with good magnetic properties is not an usual manufacturing process, so that there are not many degrees of freedom in the design and fabrication of micromagnetomechanic devices.

The design of microdevices starts from a preliminary performance evaluation, with a view to establish the range of the proper design and manufacturing requirements. In this respect, the evaluation of the mechanic characteristic of a microrelay, i.e., the dependence of the active force acting upon the moving armature of the magnetic circuit on the control current, is of foremost importance for both the overall performance evaluation and the design of appropriate driving procedures. The present paper aims at the computation of an approximate mechanic characteristic of an integrated magnetically actuated microrelay, obtained under some reasonable simplifying assumptions.

DEVICE MODEL AND SIMPLIFYING ASSUMPTIONS

The fixed magnetic circuit armature of the microrelay [1,2] is deposited on an insulator substrate as a uniform layer with protuberances surrounding an insulated meandering conductor deposition, while the moving armature of the magnetic circuit is attached to an elastic anchor (fig. 1). The device operates as a normally–open contact relay, with electrical contacts attached to the moving and fixed armatures being closed when the relay is energized at an adequate level. The detailed structure of the microrelay is presented in fig. 2, along with the relevant notations used in the following.

Some simplifying hypotheses are supposed to apply:

1°. The material of the magnetic circuit is homogeneous and magnetically linear (no saturation is reached during operation);

2°. The permeability of the magnetic circuit material is sufficiently high and the airgap is sufficiently short so that the dispersion of field lines in the airgap is negligible;

3°. The device is driven by direct current, and the operation cycle frequency is sufficiently low so that eddy currents are absent;

4°. The number of meanders is sufficiently great so that the field dispersion associated with the terminal meanders is negligible.

Moreover, it is also supposed that the concentration of the field lines in the inner arcs of the meandering current path compensates for the rarefying of the field lines in the corresponding outer arcs. Under this additional supposition, the magnetic circuit can be treated on a per unit length basis, as a two–dimensional magnetic field problem, and that means that the study of a minimal computation structure, extending over half a column of the magnetic circuit and half a cross–section of the (non–ferromagnetic) current carrying conductor, is sufficient.

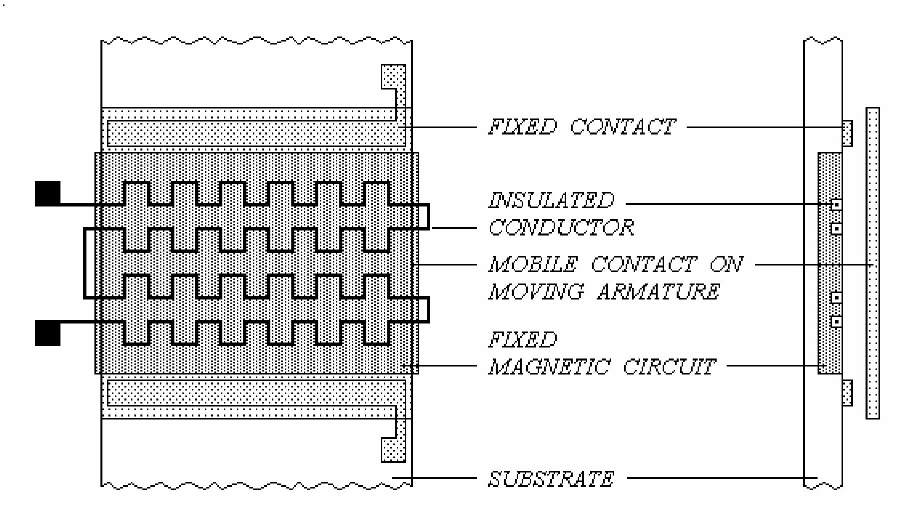

Fig. 1. Structure of the microrelay

The magnetic force per unit length acting between the armatures of the magnetic circuit in the minimal structure is computed analitically according with equation [3,4,5]

$$F = \frac{\partial W^*}{\partial z} = \frac{\partial}{\partial z}\int_S \frac{B^2}{2\mu} dS \Bigg|_{I=\text{ct.}} == \frac{\partial}{\partial z}\int_S \frac{\mu H^2}{2} dS \Bigg|_{I=\text{ct.}} \quad ,$$

where W^* is the magnetic co–energy, z is the displacement of the moving armature in the inter–contact space, S is the surface occupied by the magnetic field, and I is the energizing current. On the other hand, the finite element numerical model of the device gives the magnetic force per unit length directly in terms of the solution to the magnetic field problem.

ANALYTICAL COMPUTATION OF THE MAGNETIC FORCE

The computation of the magnetic force is based on the computation of the magnetic field strength or magnetic flux density. An analytical computation of the magnetic field is performed, considering approximate rectangular magnetic field lines around the current carrying conductor (fig. 3), which compensate the lenghtening of the field lines with a more uniform space coverage [6]. Usual simplifying hypotheses assumed in the computation of magnetic circuits are also considered: constant magnetic field strength along a field line in each given substance and uniform distribution of field lines across any cross–section.

The magnetic field, computed in terms of its flux density by applying Ampère's equation $\oint_\Gamma \boldsymbol{H} \cdot d\mathbf{r} = i_{S_\Gamma}$ along half the contour, results as

$$B_c = \frac{\mu_0 I x}{2l(2l+h)} \quad , \quad x \in [0,l] \;\text{ in conductor} \quad ,$$

$$B_a = \frac{\mu_0 I}{2[2l+h+(2+g/d+y/d)x]} \quad , \quad x \in [0,d] \;\text{ in air} \quad ,$$

$$B_f = \frac{\mu_0 I}{2\left\{ y + \dfrac{2(l+d)+g+h+2(1+H/L)x}{\mu_r} \right\}} \quad , \; x \in [0,L] \;\text{ in ferromagnetic media} \; ,$$

where $y = G+c+z$ and x is measured from the boundary of the minimal computational structure for the magnetic field in the conductor, from the conductor border for the magnetic field in air (between the conductor and the magnetic circuit column), and from the vertical border of the ferromagnetic column for the magnetic field in ferromagnetic media (fig. 3).

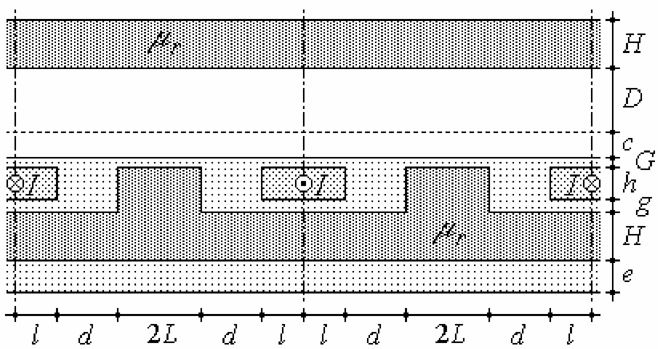

Fig. 2. Detailed structure and notations

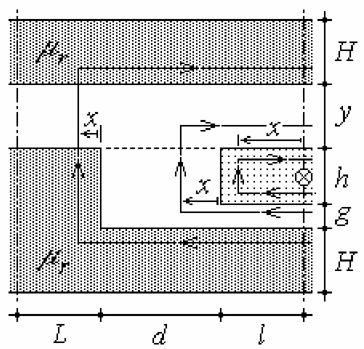

Fig. 3. Field line approximation

After computing the magnetic energy associated with each field region, the contribution of each field region of the minimal computation structure to the magnetic force per unit length is obtained as

$$F_c = 0 \quad ,$$

$$F_a = \frac{\mu_0 I}{8}\left[\frac{1}{(2+Y)^2}\left\{ \left[\frac{h+lY}{d} + \frac{(2+Y)l}{d} - \frac{2p}{d}\right]\frac{(2+Y)d}{[p+(2+Y)d]} - \right.\right.$$
$$\left. - \frac{2pY-(2+Y)(h+lY)}{[p+(2+Y)d]^2} + \frac{2}{d}\ln\left[1+\frac{(2+Y)d}{p}\right] + \frac{2Y}{p+(2+Y)d} \right\} -$$
$$\left. - \frac{2}{(2+Y)^3}\left\{ [(2+Y)(h+lY)-2pY]\frac{(2+Y)d}{[p+(2+Y)d]} + 2Y\ln\left[1+\frac{(2+Y)d}{p}\right] \right\} \right] \quad ,$$

$$F_f = \frac{\mu_0 I}{8}\frac{\mu_r L}{2q}\left[\frac{q}{(y+r/\mu_r)(y+r/\mu_r+q/\mu_r)} - \frac{(2y+2r/\mu_r+q/\mu_r)(q/\mu_r)}{(y+r/\mu_r)^2(y+r/\mu_r+q/\mu_r)^2} + \right.$$

$$+\frac{8H}{L(2+Y)^3}\left\{\left[\left(y+r/\mu_r\right)-\frac{q}{\mu_r L}(g+h+q)\right]\frac{q}{\left(y+r/\mu_r\right)\left(y+r/\mu_r+q/\mu_r\right)}-\right.$$
$$\left.-\ln\frac{y+r/\mu_r+q/\mu_r}{y+r/\mu_r}\right\}-\frac{4H}{L(2+Y)^2}\left\{\frac{2q}{\left(y+r/\mu_r\right)\left(y+r/\mu_r+q/\mu_r\right)}+\right.$$
$$\left.+\left[\left(y+r/\mu_r\right)-\frac{q}{\mu_r L}(g+h+q)\right]\frac{\left(2y+2r/\mu_r+q/\mu_r\right)\left(q/\mu_r\right)}{\left(y+r/\mu_r\right)^2\left(y+r/\mu_r+q/\mu_r\right)^2}\right\} \quad ,$$

where

$$Y=\frac{g+y}{d} \quad , \quad p=2l+h \quad , \quad q=2(L+H) \quad , \quad r=2(l+d)+g+h \quad .$$

The total force per unit length acting on the mobile armature, obtained by adding the above contributions, is multiplied by the length of the meandering structure to obtain the actual force for a reference current I. The supposed linearity of the magnetic circuit allows then to derive the mechanic characteristic of the microrelay, corresponding to actual constructive data, [1],

$$F(i)=\frac{i}{I}2NM\left(F_c+F_a+F_f\right) \quad ,$$

where N is the number of meanders of length M, and to construct the required set of mechanic characteristics (fig. 4).

NUMERICAL COMPUTATION OF THE MAGNETIC FORCE

The steady–state magnetic field of the minimal structure of the microrelay was modelled for the same numerical data corresponding to actual relay realization, [1], H = 15 μm, g = 3 μm, h = 10 μm, G = 2 μm, c = 8 μm, L = l = 35 μm, d = 50 μm, μ_r = 300, N = 64 meanders, K_e = 30 N/m. The finite element numerical method [7] was applied for discrete values only of the (relative) vertical displacement of the mobile tooth, namely z = 0 , 5 , 10 , 15 , 20 μm , and for discrete values of the driving current, namely i = 0.25 , 0.5 , 0.75 , 1 A .

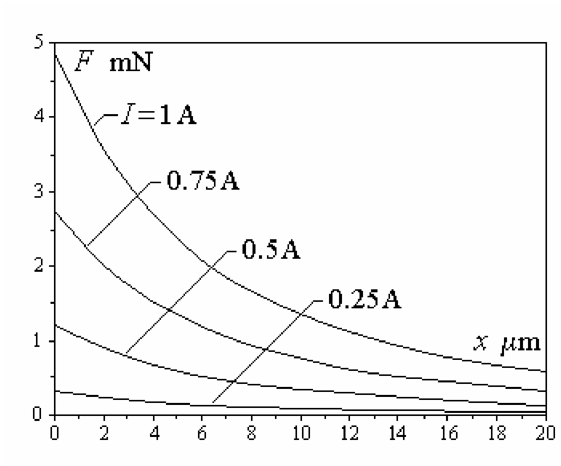

Fig. 4. Results of the analytical computation

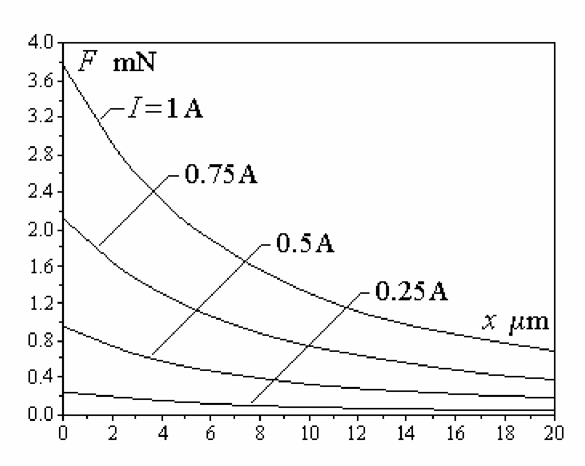

Fig. 5. Results of the numerical computation

The uniqueness conditions referring to boundary data are immediate: given (constant) magnetic potential on the upper and downer boundaries of the fixed and moving armatures, as well as on the symmetry plane of the magnetic circuit column, and homogeneous Neumann conditions on the remaining boundary. The values obtained for the magnetic force acting upon the moving armature in the 20 studied cases are used for constructing the required set of mechanic characteristics. (fig. 5).

CONCLUSIONS

The approximate mechanic characteristic of an integrated magnetically actuated microrelay was computed, under reasonable simplifying hypotheses, for data compatible with current actual realizations, by two methods: a simplified analytical method and a finite element numerical method. It can be noted that the characteristics obtained by the two methods are in good agreement.

It is worth mentioning that the numerical results obtained by following the simplified analytical procedure and the finite element numerical procedure exposed above compare successfully with other published results, [1].

ACKNOWLEDGEMENTS

Thanks are due to the staff of the Numerical Methods Laboratory, and to colleagues in the Group of Theoretical Electrical Engineering of the Electrical Engineering Department, "Politehnica" University of Bucharest.

REFERENCES

1. W. P. Taylor, O. Brand, M.G. Allen, *Fully Integrated Magnetically Actuated Micromachined Relay*, IEEE JMEMS, Vol.7, No.2, June 1998, pp. 181–191.
2. S. Coller, *Microreleu integrat*, Graduation thesis, Department of Electrical Engineering, Polytechnic University of Bucharest, 2003.
3. J. Van Bladel, *Electromagnetic Fields*, McGraw-Hill Book Company, New York, 1964.
4. H.A. Haus, J.R. Melcher, *Electromagnetic Fields and Energy*, Prentice Hall, Englewood Cliffs, J.J., 1989.
5. Anca Tomescu, F.M.G. Tomescu, R. Mãrculescu, *Bazele electrotehnicii – Câmp electromagnetic*, MatrixRom, Bucharest, 2002.
6. Anca Tomescu, F.M.G. Tomescu, *Bazele electrotehnicii – Sisteme electromagnetice* (*Lecture Notes*), Department of Electronics and Telecommunications, Polytechnic University of Bucharest, 1996.
7. Anca Tomescu, I.B.L. Tomescu, F.M.G. Tomescu, *Modelarea numericã a câmpului electro-magnetic,* MatrixRom, Bucharest, 2003.