A LINEAR ELECTROMAGNETIC SCANNING MEMS DEVICE

Cristian NECULA[1], Daniel C. COMEAGA[2], Octavian DONTU[3]

The micro-electro-mechanical systems (MEMS) are essentially miniature devices with a large field of applications including scanning applications. In this article is presented the numerical modelling process of an electromagnetic scanning device, from the mathematical modelling step for model solving. The model is an approximation of a complete electromagnetic model, very complex and difficult to solve (large computational resources and long calculus time). The model could be used for a preliminary design phase, the modelling errors being low in the defined working regime.

Keywords: MEMS devices, modelling, electromagnetic transducers, scanning device.

1. Introduction

Most of the conventional micro-electro-mechanical systems (MEMS) applications incorporate electromagnetic circuits and magnetic materials as actuating and sensing element. They offer opportunities and open new markets in information technology, automotive, biomedical fields. These systems involve miniature coils, obtained through deposition in vacuum, and permanent magnets. The magnetic materials can be deposited on micro-components and assembled in micro-devices. Additionally, magnetic MEMS devices with permanent magnets enjoy the benefits of constant energy stored in magnetic hard materials, which leads to a reduced energy consumed; also have small dimensions and simple electronic circuit, compared with an electromagnetic transducer, using only miniature coils [1-3]. Experimental, numerical modelling, and fabrication technology for electromagnetic bending-mode cantilever transducers are presented in [4-6]. The MEMS systems based on magnetic interactions between magnetic materials and electric coils can be widely used because they offer advantages compared to electrostatic transducers regarding generated force and displacement. One common application of MEMS devices is scanning. The scanners are used in

[1] PhDStudent, Dep. Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, Romania, e-mail: cristianecula@yahoo.com
[2] Prof., Dep. Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, Romania, e-mail: comeaga@hotmail.com
[3] Prof., Dep. Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, Romania, e-mail: octavdontu@yahoo.com

a large set of application from entertainment (virtual reality devices) to medical systems (optical system for non-invasive surgery). Also, MEMS scanners are of special interest for medical imaging applications. Other domains, which benefit from MEMS scanners development, are confocal microscopy, [7] barcode reading, [8] fingerprint sensing, [9] optical cross-connects technology [10], optical coherence spectroscopy [11], printing, light detection and ranging systems for automotive industry [12]. The first laser scanning mirror using MEMS technology was announced in 1980 [13]. Previously were studied different technical solutions for acquiring scanning with different actuating principles (electrostatic, electromagnetic, electrodynamic, thermal). Each has specific advantages and disadvantages. The electrostatic principle allows a very low dimension but the displacements are extremely low [14,15]. Piezoelectric transducers [16,17] using composite multi-layered structures provide high forces but also a strong increase of stiffness and the resonant frequencies. The thermal actuation could have large amplitudes but is difficult to control and is extremely slow [18,19]. The electrodynamic transducer requests a mobile coil having the difficulty to create flexible electrical supplying circuits but offer large amplitudes and a linear behaviour. The electromagnetic system is larger, heavier but with large deflections and the electrical supply path is fixed.

2. Design and numerical modelling of a magnetic micro transducer

In this study are presented the modelling and the results of numerical simulation for a magnetic micro transducer type BCMS (bending-mode cantilever micro transducers).

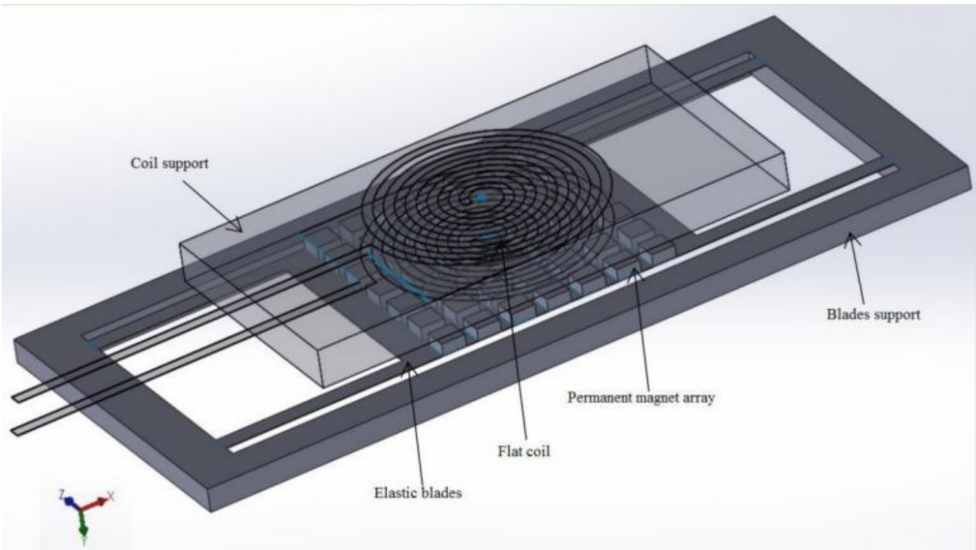


Fig. 1. a) 3D CAD model of the micro transducer

It has been studied a concept of cantilever transducer provided with an array of permanent magnets placed on a rigid and mobile plate connected with the device rim using four elastic blades, which are constructed of a beryllium copper.

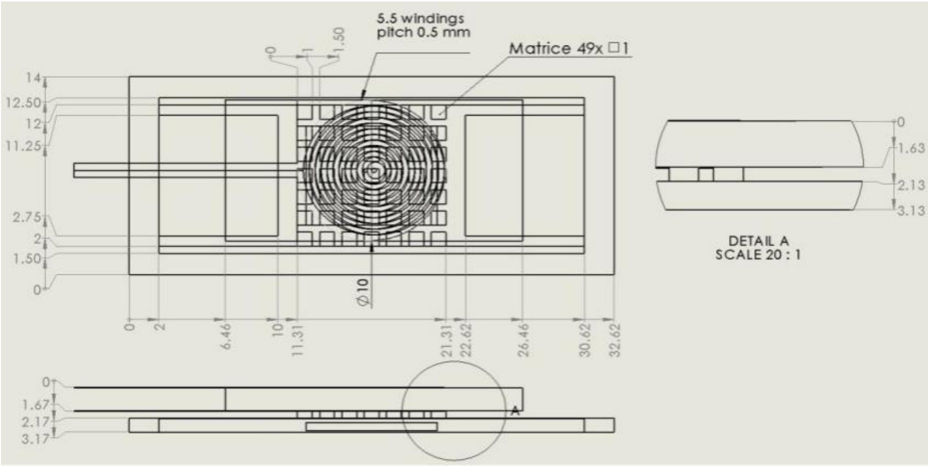


Fig. 1. b) Dimensions of the micro transducers

The magnets array interacts with the magnetic field produced by electric current flowing through the planar spiral coil placed on a base plate made of silicon. The design is based on a previous solution with 1 set of blades and having a combined type of movements (translation and rotation) for the magnets support.

In order to achieve oscillatory motion, it has to exist an applied force and a restoring force. The applied force depends on the magnetic field of the coil as well as the permanent magnetic field of magnets. The applied force is directly influenced by the array of permanent magnets position in relation to the coil.

During this stage, is supposed the mathematical models that describe physical effects being coupled only into one "sense" - the magnetic field does not change the distribution of electric current in the coil and structural deformations does not change the magnetic field distribution system.

This is the case of a scanner working below the resonance. The resonant scanner design will be considered in the next stage and will be subject of another article. Numerical simulation is conducted on 3D calculation. In the first study is resolved an overall electro-kinetic problem, to determine the distribution of electrical current conduction density through the coil, and then is evaluated the magnetic field produced by this current distribution. The magnetic forces due to the interaction of this field with the permanent magnets are then computed using a magnetic field study.

The magnetic forces are applied, and their effect is evaluated using the third structural study, and allow to evaluate the deformations of the elastic structure carrying the magnets array.

3. Exact analysis for electromagnetic device

3.1. The mathematical model

The electromagnetic field is propagated indefinitely in space and is one of the main cause of forces, being the base for all electrical actuation solutions. At high rates, the very fast variation of the electrical and magnetic fields conducted to a reciprocal influence of them, reflected by associated terms in the Maxwell–Lorentz equations, other than the field produced by sources (electrical charge and current flows) [20]. In this case, the process is extremely low so the field interactions were neglected. Also due to the deformations are very low (of micrometres order of magnitude) the reciprocal influence could be neglected (the deformations are not influencing the magnetic field forces and this is not influencing the current flow through the coil). The electric field is the effect of electrical potentials applied to the coils terminal and this is producing an electrical current that crosses the stationary conductor. The electrical current distribution is producing the magnetic field.

3.2. The stationary electromagnetic field

On the assumption of a stationary regime, the problems of an electric and magnetic field are separable. The electrokinetic field is described in [20]:

$$\nabla \cdot \left(\sigma_{el} \nabla V\right) = 0 \tag{1}$$

where:

V- is the electric potential [V];

σ_{el} - is electrical conductivity [S/m].

This problem is solved only in volume coil. The model boundary conditions are:

a) the coil surface is electrically insulated;

b) one of the terminals of the coil has a potential V = 0 V (ground) and at the other terminal is given by electric current density, ($\mathbf{J}_n$ = 0,…,5 A/mm^2) or an electric potential.

Each case corresponds to an electronic control method – current or voltage control. The connection between electric conduction current density and electric potential is given by electrical conduction in linear environmental, homogeneous and isotropic $\mathbf{J} = -\sigma_{el} \nabla V$. Electric current density is along with permanent magnets residual induction, Br [T] the source of the magnetic field [5].

$$\nabla \times \left(\mu_0^{-1} \mu_r^{-1} \nabla \times \mathbf{A} - \mathbf{B}_r\right) = \mathbf{J} \tag{2}$$

where:

A - is the magnetic potential, total vector (is being used the Coulomb condition of calibration [20] [T x m];

$\mu_0 = 4\pi \times 10^{-7}$ H/m - is the magnetic permeability of vacuum;

μ_r - is the relative magnetic permeability.

The boundary condition that completes the mathematical model is magnetic insulation (n *x* A = 0, where *n* is the outward normal) along the border area calculation. The mathematical model (1)-(2) was solved numerically. Determination of magnetic field actions requires determining of magnetic impulse tensor (Maxwell), $\overline{\overline{T}}_{mg}$ [N/m^2] or determination of magnetic energy density distribution w_{mg} [J/m^3] and use the theorem of generalized forces, $\mathbf{f}_{EM} = \nabla \cdot \overline{\overline{T}}_{mg}$ or $\mathbf{f}_{EM} = \nabla w_{mg}$ [N/m^3]. The magnets array is oriented with the residual induction, Br, in the *xOy* plane parallel to the blades (the plane of the elastic blades). The magnetic field produced by the permanent magnets interacts with the magnetic field produced by the current flowing through coils. The result is a force that produces blade deformation. It is really necessary that the force should be repulsive. Blade deformation is analyzed in terms of stationary study. The transducer substrate is made of silicon, the coil windings are made of copper and permanent magnets are made of NdFeB. The PI cantilever has a lower modulus of elasticity, which allows a large deflection angle. Table 1 illustrates the properties of structural BCM parts.

Table 1

The electric, magnetic and mechanical properties of BCM

Material	*E* [GPa] (1)	n (2)	r_{st} [kg/m^3] (3)	m_r (4)	B_r [T] (5)	e_r (6)	s [S/m] (7)
Elastic blades (PI)	2.94	0.35	1410	1	—	3.4	6700
Support (silicon)	170	0.28	2329	1	—	12.1	—
Winding (copper)	128	0.35	8700	1	—	1	$5.998 \cdot 10^7$
Permanent magnets (NdFeB)	245	0.281	7500	1.1	1.3	1.05	$7.143 \cdot 10^5$

(1) Young's modulus; (2) Poisson ratio; (3) Mass density; (4) The relative magnetic permeability; (5) Residual induction; (6) Electrical permittivity; (7) Electrical conductivity.

3.3. Solving coupled simulation (electro-kinetic field, magnetic field and structural problem)

Solving the problem of an electric field is made in the "*Electric Currents*" section of Comsol 5.0 software, by declaring as input the voltages applied on certain surfaces and lines. In this case, the control voltage $U_b = 0.022$ V parameter applied is declared, on one terminal of the coil and also a ground terminal on the other end of the coil.

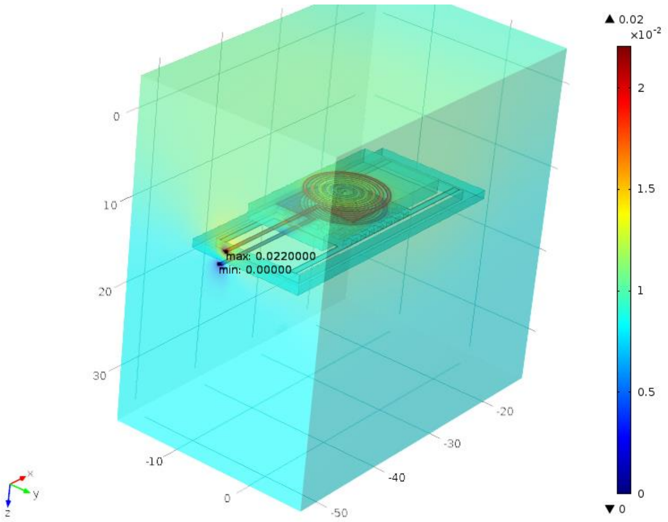


Fig. 2. The electrical potential (V)

Using terminals declarations and not only voltage declarations allow to automatically evaluate the discrete electrical parameters of the equivalent circuit, (fig. 2). After numerical simulations, it was obtained in the flat coil a maximum current density of 8.7506 x 10^6 A/mm^2, similar with the limits for printed circuit boards (fig. 3).

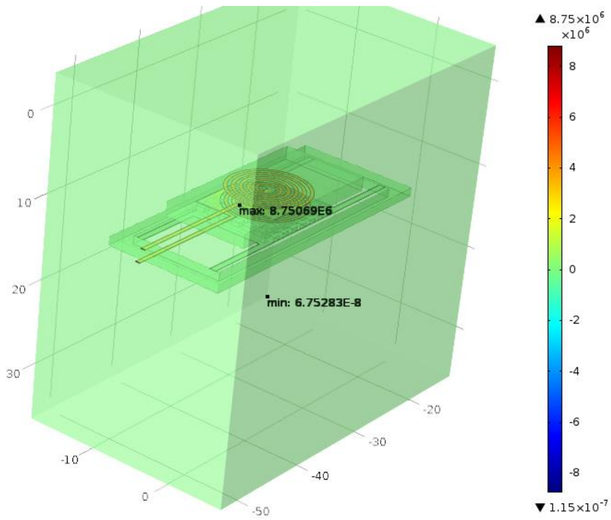


Fig. 3. Current density norm (A/mm^2)

In the next step, the solver computes the magnetic vector potential, magnetic field intensity and magnetic flux density and magnetic forces. In fig. 4 are presented the strains and deformations determined by numerical simulation. The overall force acting on the magnetic matrix produced a displacement blade by 2.13 mm, on *Oz* direction, with von Mises stress equivalent to 7.498 x 10^8 N/m^2 (fig. 5) close to the von Mises stress limit of 7.50 x 10^8 N/m^2 specific to beryllium copper, for residual induction, B_r oriented in the *Ox* direction.

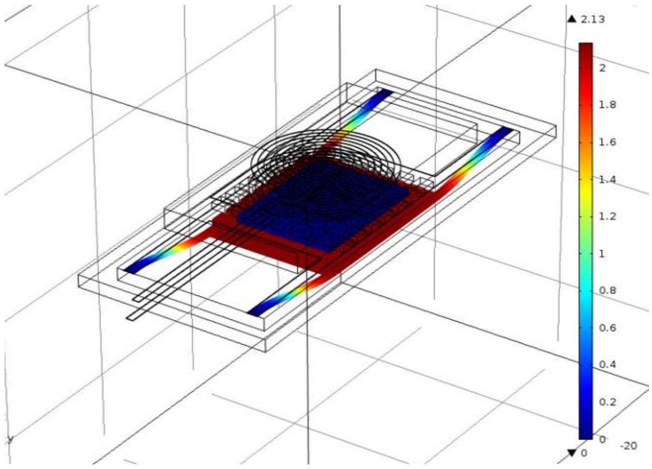


Fig. 4. The displacements of elastic blades (spatial)

The electric current that passes through the coil creates a magnetic field around it. This magnetic field creates an induced current in the coil, so the inductance is equal to 0.6 H and the electrical resistance is 0.143 Ω.

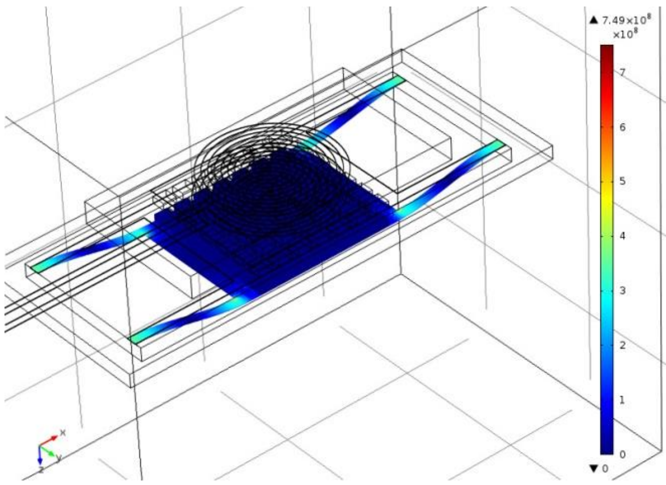


Fig. 5. The von Mises stress of elastic blades

3.4. The modal behavior

In designing and obtaining the most dynamic control, it is essential to perform a modal analysis. The purpose of these experimental research was to prevent the structural instability that may occur under normal operating conditions. It is important to avoid using the electromagnetic transducer under operating conditions around these frequency ranges to reduce the risk of entering the resonance zone**.** The modal analysis is the method for determining the modal parameters corresponding to the magnetic matrix flexible structure (frequency, damping and modal) for all of its own oscillation modes in the field of interest. The aim was to get the frequency response of the transducer. Any dynamic deformation produced in its structure is represented by a weighted sum of the forms of its own oscillation modes.

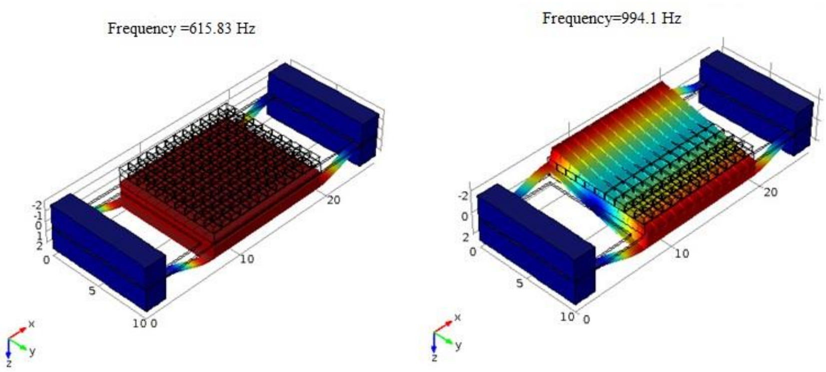
Evaluation is important because quasi-static scanning systems are designed to operate at frequencies of up to 80-90% of the first resonance frequency. However, there is also the possibility of creating a scanning system that is viable at the resonant frequency of the flexible structure, with the advantage of very large displacements even at significantly lower input force amplitudes compared to the static mode. Not every kind of oscillation can be used. In this case, it is of interest only the ways in which the surface of the area with magnets does not deform significantly, while at the same time assuring an oscillation movement thereof around an axis (but a known translational movement of the axis).

Before going through the modal analysis methodology, the type of matrix loading with permanent magnets should be determined. During the design stages, we encountered a problem with the force system acting on the magnetic matrix. There has been a question of choosing between the following methods of action:

a) the use of a concentrated load;
b) application of a distributed force across the magnetic matrix surface.

If a distribution load is applied, the resulting force is obtained by calculating the magnetic matrix area, the force arm being measured between its centre of gravity and its reference point. The experimental study was conducted using a focused parameter model to obtain a quick calculation solution. The applied method was as follows: Embed the flexible structure at the opposite end of the matrix with magnets.

To determine the proper modes corresponding to the resonance frequencies and the electromagnetic fields, we use the *Eigenfrequency* module in the Comsol program. As mentioned before the model is valid as time as the movement is far under the resonant behaviour. The useful frequency range for transducer control is limited by the first *eigenfrequency*. In fig. 6 a),b) are presented the first two resonances, the control frequency being limited to 615.83 Hz, covering the necessary frequency range.



a) b)

Fig. 6. The first two resonances a) f~615.85 Hz b) f~994.1 Hz

The purpose of this modal analysis is to obtain the most efficient dynamic control to achieve a prototype electromagnetic transducer. It is necessary to avoid structural instability that may occur under normal operating conditions. For a more accurate analysis of how the transducer behaves in relation to the frequency, we have increased the resolution across the frequency range to accurately determine the resonance area of the electromagnetic transducer.

Fig. 7. The stages of resonance evaluation and determination of mechanical response

Before performing the numerical simulations, we determined the elastic modulus specific to the CuBe alloy. Frequency response was also derived experimentally. The elastic blade was fixed on an oscillating system (using piezoelectric actuation) to measure the oscillation response with a differential laser vibrometer.

The laser beam was focused at the free end of the blade. Laser beam oscillations were received with an accelerometer. The laser vibrometer is part of an MSA400 microsystem analyzer, which also contains a signal generator, the spectral response frequency of the mechanical transmissibility was obtained, which allowed the evaluation of the resonance frequency, the final result concluded by the elastic modulus evaluation (the density was calculated by measuring the mass and volume of a sample from the same material).

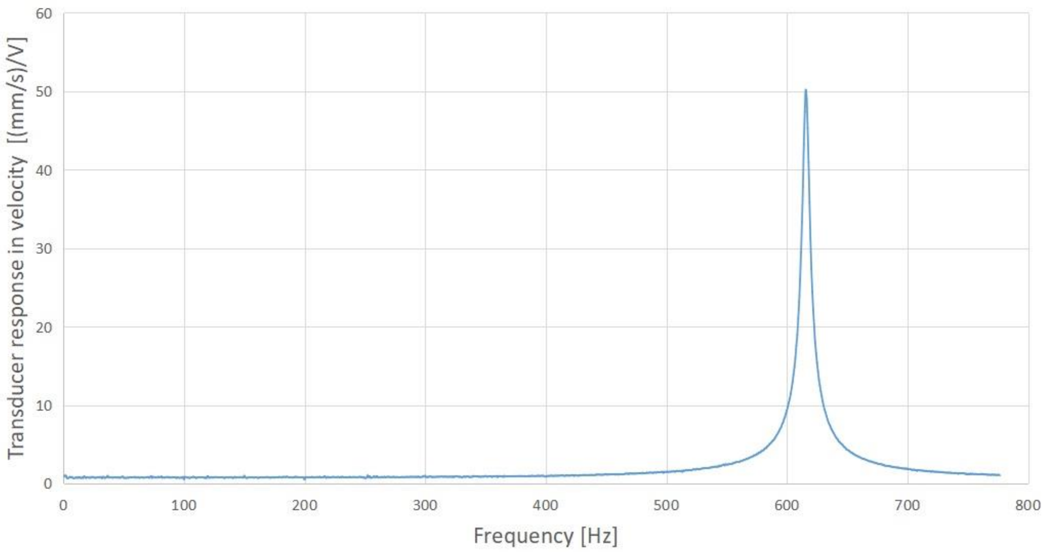


Fig. 8. The characteristic between velocity and control voltage in relation to the frequency range; micro transducer response in the frequency

As a result of the measurements, the electromagnetic transducer reaches the resistance area at a peak frequency of 615.83 Hz. The speed response for the elastic blade is 50.14 [(mm/s)/V] fig. 8. The response obtained in the resonance frequency determined a magnetic matrix shift equal to 0.0138 mm (mm/V).

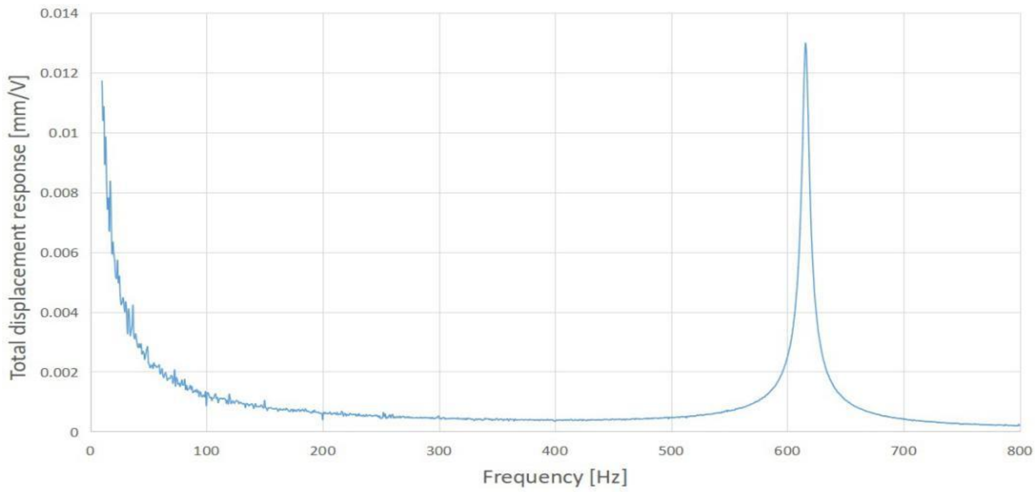


Fig. 9. The characteristic between displacement and control voltage in relation to the frequency range; the micro transducer response in the frequency

4. Conclusions

In this study was performed mathematical modelling and numerical simulation of electromagnetic interactions that occur in a cantilever transducer with elastic blades, in quasi-stationary study conditions, used for low-frequency linear scanners. The deflection of flexible blades can be controlled by adjusting the electric current in the flat coil. The stationary electromagnetic field model and the structural model are one-way couplings. Therefore, the electromagnetic forces represent input data used in the structural analysis. The 3D modelling can give an estimate within the meaning orders of magnitude of electrodynamic forces and mechanical deformations. Modal analysis is essential in the designing and dynamic control of a BCM, to avoid structural instability that can occur in normal working conditions.

Acknowledgments

The authors acknowledge professor Alexandru Morega from University Politehnica of Bucharest for the permanent support offered during this work. This work was supported through the PN-II-PT-PCCA-2013-4-1557 Research Grant, entitled "Electromagnetic and Electrodynamic Actuators Processed Through LIGA Technology", by the Executive Unit for Financing Higher Education, Research, Development and Innovation (UEFISCDI).

R E F E R E N C E S

[1]. *L.K. Lagorce*, et.all., "Magnetic Microactuators Based on Polymer Magnets", IEEE J.Microelectromesh. Syst., **Vol. 8**, No. 1, 1999, pp. 2-9.

[2]. *B.M. Dutoit*, et. al, "High Performance Micromachined Sm2Co17 Polymer Bonded Magnets",Sensors and Anctuators 77, 1999, pp. 178-182.

[3]. *O.Cugat* et. al, "Deformable Magnetic Mirror for Adaptive Optics", Proc. IEEE MEMS 2000,Myyazaki, Japan, 2000, pp 485-490.

[4]. *C.T. Pan*, P.J. Cheng, C.K. Yen, and C.C. Hsieh, "Application of polyimide to bending-mode microactuators with Ni/Fe and Fe/Pt magnet", *Microelectronics Reliability*, **vol. 46**, pp. 1369-1381, 2006.

[5]. *J.M. Zara* and P.E. Patterson, "Polyimide amplified piezoelectric scanning mirror for spectral domain optical coherence tomography", Applied Physics Letters, **vol. 89**, Applied Biophysics, 2006.

[6]. *C.T. Pan,* P.J. Cheng, M.F. Chen, and C.K. Yen, "Intermediate wafer level bonding and interface behavior", Microelectronics Reliability, **vol. 45,** pp. 657-663, 2005.

[7]. *D. L. Dickensheets*, and G. S. Kino, "Silicon-micromachined scanning confocal optical microscope," J. Microelectromech. Syst., **vol. 7** (1), pp. 38–47, Mar. 1998.

[8]. *S. O. Isikman*, R. B. Sprague, and H. Urey, "FR4 laser scanner with dynamic focus," IEEE Photon. Technology Letter, **vol. 21** (4), pp. 233–235, 2009.

[9]. *A. P. Neukermans* and T. G. Slater, "Micromachined torsional scanner," U.S. Patent 5 629 790, May 13, 1997.

[10]. V. A. Aksyuk, F. Pardo, C. A. Bolle, S. Arney, C. R. Giles, and D. J. Bishop, "Lucent microstar micromirror array technology for large optical crossconnects," Proc. SPIE, **vol. 4178**, pp. 320–324, 2000.

[11]. *Y. Pan*, H. Xie, and G. K. Fedder, "Endoscopic optical coherence tomography based on a microelectromechanical mirror," Opt. Lett., **vol. 26** (24), pp. 1966–1968, 2001.

[12]. *U. Hofmann,* F. Senger, F. Soerensen, V. Stenchly, B. Jensen, and J. Janes, "Biaxial resonant 7 mm-MEMS mirror for automotive LIDAR application," in Proc. Int. Conf. Opt. MEMS Nanophoton., Banff, AB, Canada, pp. 150–151, 2012.

[13]. *K.E.Petersen*, "Silicon torsional scanning mirror", IBM J. Res. Develop**, vol. 24** (5), pp. 631-637, 1980;

[14]. *A. Selvakumar*, K. Najafi, W. H. Juan, and S. Pang, "Vertical comb array microactuators," in Proc. IEEE MEMS, Amsterdam, The Netherlands, Jan./Feb. 1995, pp. 43–48.

[15]. *E. S. Hung* and S. D. Senturia, "Extending the travel range of analog tuned electrostatic actuators," J. Microelectromech. Syst., **vol. 8**, no. 4, pp. 497–505, 1999.

[16]. *P. Muralt*, A. Kholkin, M. Kohli, and T. Maeder, "Piezoelectric actuation of PZT thin-film diaphragms at static and resonant conditions," Sens. Actuators A, Phys., **vol. 53**, pp. 398–404, 1996.

[17]. *M. Tani*, M. Akamatsu, Y. Yasuda, H. Fujita, and H. Toshiyoshi, "A combination of fast resonant mode and slow static deflection of SOI-PZT actuators for MEMS image projection display," in Proc. IEEE/LEOS Int. Conf. Opt. MEMS Appl. Conf., Big Sky, MT, USA, pp. 25–26, 2006.

[18]. *Y. Xu,* J. Singh, T. Selvaratnam, and N. Chen, "Two-axis gimbal-less electrothermal micromirror for large-angle circumferential scanning," IEEE J. Sel. Topics Quantum Electron., **vol. 15** , pp. 1432–1438, 2009.

[19]. *L. Li,* R. Bauer, G. Brown, and D. Uttamchandani, "A symmetric hybrid MEMS scanner with electrothermal and electrostatic actuators," in Proc. IEEE Opt. MEMS Nanophoton., Istanbul, Turkey, pp. 163–164, 2011.

[20]. *C.I. Mocanu,* Electromagnetic Field Theory, 2nd ed. in Romanian, Ed.D.P. Bucuresti 1982.