A Novel Concept of Electromagnetic Pressure Sensor based on Impedance Variation for Pneumatic Applications

Popescu-Cuta Alina [1,a], Comeaga Constantin Daniel [1] and Dobre Alin Alexandru [2]

[1] *University POLITEHNICA of Bucharest, Mechatronics and precision Engineering Department*
[2] *University POLITEHNICA of Bucharest, Electric Machines, Materials and Drives Department*

Abstract. The core concept of the proposed sensor relies on the architecture of a new type of microscale electromagnetic actuator, previously developed and tested. Previous studies were focus on conceptual design, modelling and simulation and application as an actuator for static and dynamic purposes. Upon presenting the device functioning principle and design, the authors propose a new application of this device, as a detection element, due to its electrodynamic behavior that allows the correlation of displacements and deformations with the variation of the device coil inductance. This dependency could also be used as a feedback information, allowing a closed loop control without an aditional sensorial element. A series of numerical models have been developed and computed in order to test the sensorial properties of the device and to describe the functioning principle as a detection element. The models have been computed using two materials for the sensor's mobile element, to test if the manufacturing costs can be lowered by using a material without magnetic properties and the conclusions of the studies have also been drawn. Once the sensor behavior and the structural materials have been concluded, a sensor model has been developed and studied using FEM. Further on, one of the sensor constructive parameters has been varied in relation to the desired measuring range and the future research directions have been drawn.

1 Introduction

The paper presents a novel concept of an electromagnetic pressure microsensor, designed for low pressure pneumatic applications. The core concept of this sensor took shape when was proposed a new type of MEMS electromagnetic actuator [1,2] consisting of a cantilever with a micro-magnets array at its free end and a fixed planar coil or set of coils, disposed parallel with the cantilever and positioned at a fixed distance from it (Fig. 1). The device used the common principle of electromagnets actuators, adding the design and manufacturing at micro-scale and also an improvement by using a magnetic layer, deposited by electro-deposition, on the elastic cantilever. Previous studies shown by simulation and also through experiments a detectable variation of coil inductance, depending on the displacements and deformations [3]. Initially seen as a perturbation for the command electronics, producing disturbances in the control signal, this coil inductance variation proved useful as a sensorial information. A feedback loop is possible, using the detected inductance variation as a feedback signal for controlling the actuator position. Transforming the actuator is possible to used it as a pressure sensor, with two possible design. The first design is robust, using stiff magnet, and it is only a reversal of previous actuator use. A design is proposed herein and simulations are included, showing a relevant and detectable, with the actual electronic circuits, inductance variation. This type of sensor has a main disadvantage in his bulk magnet, conducting to low resonant frequency and limiting the useful frequency range. The second design use a very thin magnetic layer and allow it to deforme under external pressure, toghether with the suporting membrane. This design is not possible at macro-scale but became possible at micro-scale using thin magnetic layers obtained through electro-deposition.

Another functioning is possible, rarely seen in common sensors but used for advanced accelerometers, based on the dual use of the system as actuator and sensor. The system is deformed or displaced under external signal (pressure, acceleration, etc.), conducting to some parameters variation (resistance, inductance) detected by the electronics and transformed in an analog sensorial signal. This parameter variation is not used as a sensorial signal but as a feedback signal for the actuator control. The actuator then tends to compensate the externally produced variation of position and move back to the equilibrum position. Even more expensive then common sensors, which output the sensorial signal, this feedback-based sensors are more precise, having a low sensitivity to external disturbances and wider frequency range, being also less sensitive to noise.

The sensors based on strain bridges, with electrical resistance, and other type of materials without actuating potential cannot be used as feedback sensors. But the

[a] Corresponding author: alina_popescu2704@yahoo.com

electrodynamic, capacitive and piezoelectric sensors are feasible for this application. The cheaper and easiest to manufacture sensors are the ones based on piezoelectric phenomenon but lack of the static behaviour (even having the possibility to be used up to very high frequency, in the MHz domain). The capacitive sensors could be used for static and also dynamic purposes but requests very small distances between the plates and subsequently a very expensive technology as X-ray LIGA or semiconductor specific technological processes.

The main reasons the authors chosed an electrodynamic interaction as an actuating/sensorial method are the wide range of displacements and strength at micro-scale [4] and because electromagnetic actuators also provide the best energy-volume ratio which makes them ideal for MEMS applications. This are combined with affordable and easy to use technologies.

The electromagnetic (EM) actuators/sensors have complex structures but develop high forces at any scale, and can be used at resonance or far from it [5]. A very important argument in using EM actuated scanners is the lower sensitivity to dimensional imperfections.

The common design use a fixed magnet and a mobile coil. Previous studies proved the possibility to build thin magnetic layer, in continnous or matrix-type design, directly on the mobile part. The chosen actuator design, with a fixed coil and moving magnets has eliminated the issues arisen by supplying current to a moving coil. The authors have also tested various coil configurations and obtained the electric current – displacement characteristic for each of them, in order to determine the appropriate design for a micro-scale actuator functioning based on electrodynamic principles [1-3] (Figure 1).

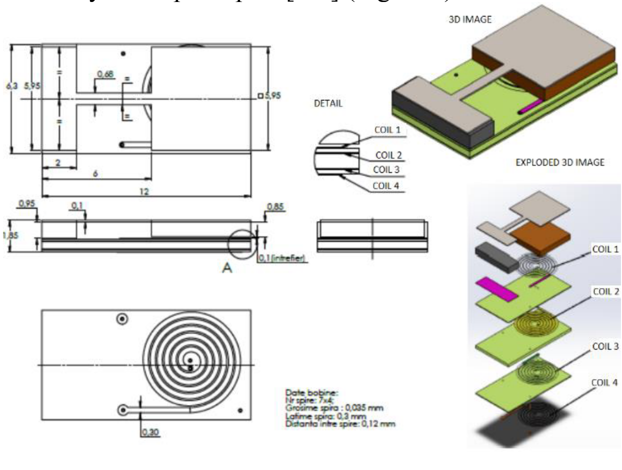

Figure 1. The design of the electromagnetic actuator.

Upon studying the electric current – displacement characteristics and the actuator design, was determined that the device behavior provides potential sensing properties and the actuator could also be used for detection purposes, besides the ones that it was initially designed for. Given that an electric current supplied to the coil generates a displacement of the cantilever free edge, through the electrodynamic interaction with the magnets on the cantilever, the main objective of this paper became to test the influence of the moving magnets over the electrical parameters of the coil. Since the device dimensions are very small, measuring the current induced by the moving magnets would require a complex setup, that does not match the low cost and usability of MEMS systems. Therefore, the paper studies the influence of the moving magnets over the coil inductance, with the purpose of obtaining a linear variation of inductance with the input displacement. The original actuator could therefore be used also as a low pressure sensor for pneumatic applications, in which fluid pressure can be maintained at lower values compared to hydraulic systems.

2 Design and functioning

2.1 Modelling and simulation of non-magnetic device

The first step of the research consisted of determining the coil inductance variation in relation to the position of the mobile plate. In the original actuator model, NdFeB was used as magnetic material, but its costs are relatively high [1-3], due to the fact that it belongs to the rare earth magnetic materials. Therefore, in an attempt to lower the device costs, the magnetic material has been initially replaced with a high magnetic permeability steel alloy and a numerical model has been created in order to determine the variation of inductance with the position of the metallic plate.

The coil model has been created using the SolidWorks 2016 software (Fig. 2, a)) and has been further imported to Comsol Multiphysics in order to compute the numerical model. Once imported to Comsol, the model has been surrounded by a prismatic volume of air in order to delimitate magnetic lines in the electromagnetic simulations. A metallic plate has also been added parallel to the coil, at a distance that was parametrically defined (Fig. 2, b)). The simulations are carried with the purpose of determining the influence of a mobile plate over the coil inductance.

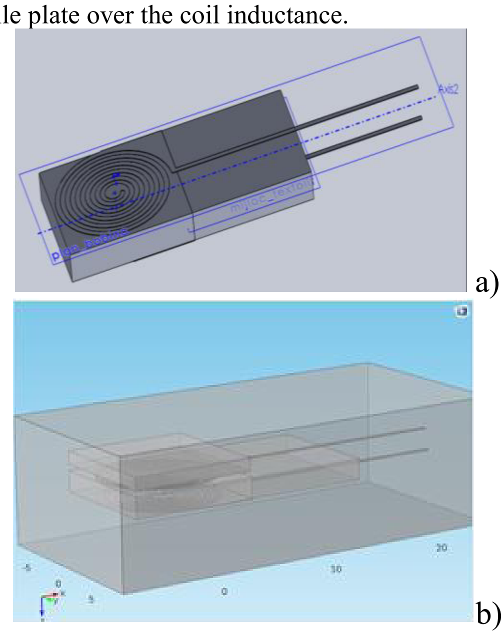

Figure 2. Design of the actuator/sensorr: a) coil design, b) the coil, mobile plate and the air volume .

The mobile plate thickness has been initially set to 0.5 mm and the distance between the metallic mobile plate and the coil has been incrementally increased with 0.1 mm, starting from 0.1 to 1 mm. Several phenomena concur in the functioning of the device, requiring an integrate or a step-by-step modelling, described through a sequence of coupled problems that are solved in turn. Two modelling were chosen: one integrate and one step-by step. For the first part of the article, involving a rigid magnet, the step-by-step procedure was preferred due to flexibility and computing time.

In the step-by-step modelling, the electric and magnetic phenomenon were considered uni-directionally coupled, the electric current influencing, through the current density created, the magnetic field and subsequently the forces acting on the plate. First, a stationary (electrokinetic) problem is solved to compute the electric field in the coils and the current density. The electrical current density thus obtained is used as input (field source) to a stationary magnetic – which is solved to find the electrodynamic forces. The models are coupled just in a "one-way" time arrow: the magnetic field does not influence the electric current density distribution in the coil. For the sensor behaviour simulation, based on detection of inductance variation due to plate position, only these steps are necessary. For the functioning with feedback simulation another step is necessary, to compute the cantilever deflection that occur.

The equations used are (electro-magnetic fields):

- the first electrokinetic problem for the electrical field (for the electrical field inside the coil):

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

where V [V] is the electric potential and σ_{el} [S/m] is the electrical conductivity. Only the volume of the coil was chosen as the computational domain for (1). The boundary conditions that close (1) are: electrical insulation for the coil surface ($\mathbf{n}\cdot\nabla V=0$), ground (V = 0 V) for one of its terminals, and an external voltage for the second terminal (V = 20 mV). The electrical conduction law in conductors for linear, homogeneous, isotropic media without impressed electric fields, provide for the electric current density. The electrical current density is the source for the magnetic field problem [6]:

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

where A [T • m] is the total magnetic vector potential, $\mu_0 = 4\pi\times10\text{-}7$ H/m the magnetic permeability of the free space, and μr the relative magnetic permeability of the different materials. The boundary condition for (2) is magnetic insulation (n × A = 0, where n is the outer normal) for the outer surface of the computational domain – here, a parallelepiped that is large enough to contain the device such as to close the magnetic field.

Problems (1) and (2) were solved numerical using the finite element method (FEM) [7]. The mobile plate thickness has been initially set to 0.5 mm and the distance between the metallic mobile plate and the coil has been incrementally increased with 0.1 mm, from 0.1 to 1 mm.

A parametric stationary study has been carried out, in order to determine the coil inductance at various positions of the metallic plate (Fig. 3).

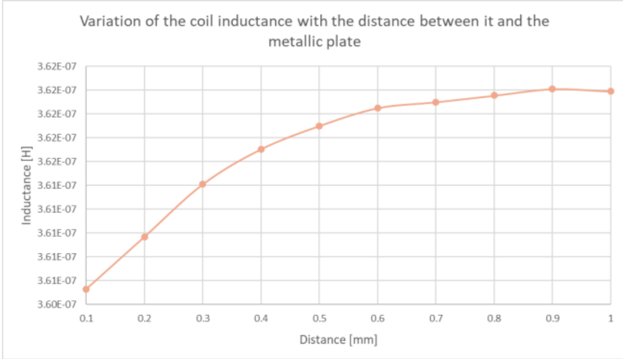

Figure 3. The variation of the coil inductance with the position of the mobile plate.

The nonlinear variation of inductance with the metallic plate position could be caused by a potential alteration of the magnetic field lines with the plate displacement and will be the subject of future research, but even if median values are extracted from the chart, there is no possibility to obtain a linear variation of inductance with the metal plate displacement. The coil inductance variation is extremely low and not useful. Also the magnetic forces acting on the plate are very low and unable to compensate an external pressure of common values specific to pneumatics. The results are similar with the conclusions derived at the design stage. The improvement proposed and proved feasible was to replace the metallic plate with a magnetic one.

2.2 Modelling and simulation of magnetic device

Given the results obtained with a metallic plate, the same model was computed again, this time using a magnetic material (NdFeB). The first simulation step is similar but the second is completed with a new condition. An Ampere's Law condition has been added, in order to define the magnetization, with a value of 1.3 T on the X axis (previous studies proved the in-plane magnetization is superior in term of stability to a magnetization perpendicular to plate [4]).

The Equation 2 is completed with a term describing the permanent magnetization in the plate:

$$\nabla\times\left(\mu_0^{-1}\mu_r^{-1}\nabla\times\mathbf{A}-\mathbf{B}_r\right)=\mathbf{J}, \quad (3)$$

The magnetic field obtained is presented in Fig. 4 .

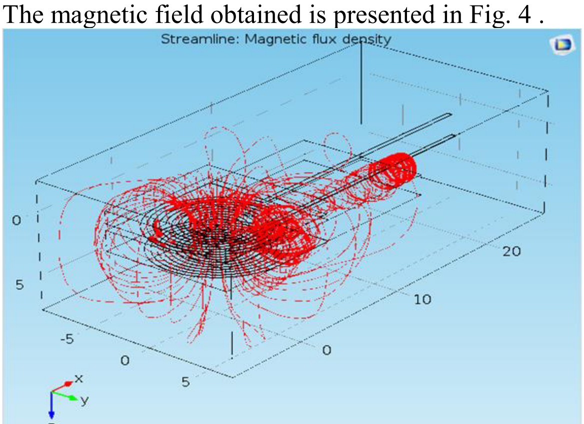

Figure 4. Magnetic field lines.

The coil inductance could be computed through the use of total magnetic energy or using small perturbations, at specified frequencies, applied over static problem. The first method is eroneous due to the high magnetic energi produced by the magnetizied plate. The second methos is more precise, even requesting high computation time.

The coil inductance variation with the position of the magnetic plate is presented in Fig. 5.

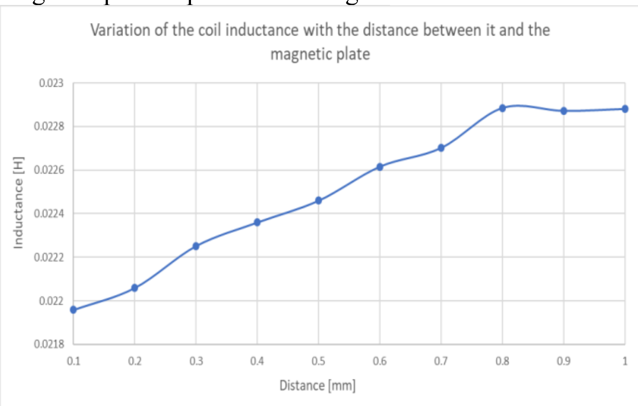

Figure 5. The coil inductance variation.

According to figure 5, the coil inductance increases with the distance between the coil and the magnetic plate, until the distance is too high to have a relevant influence. The variation is described by the equation (4), that is applicable until the mobile plate is positioned at 0.8 mm from the coil. Beyond this value, the influence of the magnetic plate over the coil inductance becomes constant, therefore 0.1 - 0.8 mm will be the measuring range of the sensor.

$$L[T] = 11*10^{-4}*d[mm] + 219*10^{-4} \quad (4)$$

The variation is cvasi-linear over a wide range of displacements, and allow to built the sensor.

Due to dimensional restrictions in designing the sensor is common to have a displacement of the magnet, placed on a deformable element under the external pressure, of maximum 100µm, producing a variation of inductance of 0.2 µH, possible to be detected using a circuit with shifting of resonant frequency.

2.3 Optimization of the magnetic device

The proposed sensor can currently be used for low pressure pneumatic applications, as the ones currently used in medical technologies. An optimization for higher pressures would involve using a thicker membrane, but this involve a lower resonant frequency and higher inertial forces due to shocks, making possible a membrane degradation. Therefore, an optimal thickness of the mobile plate needs to be determined in order to obtain a vertical displacement of the magnetic element with no plastic deformation.

It is expected that by varying the magnetic plate thickness at several interstices between the plate and the coil will result in several thickness – inductance curves that will translate depending on the position of the mobile plate. Therefore, another numerical model has been built in order to determine the coil inductance variation for several magnetic plate thicknesses at a median distance between the mobile plate and the coil. The results of the study are presented in Figure 6.

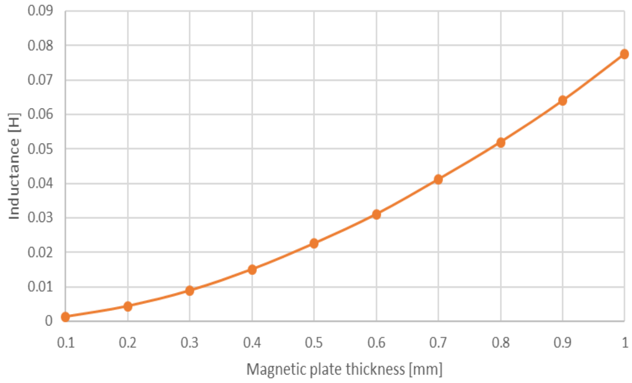

Figure 6. The variation of the coil inductance with the magnetic plate thickness.

By analyzing the graph in Fig. 6, it can be concluded that increasing the thickness of the mobile plate also results in a cvasi-linear increase of the coil inductance.

2.4 Modelling and simulation of deformable magnetic device

The previous solution produce very small inductance variations. A study regarding the possibility to obtain an increase of inductance by allowing the magnetic material to be deformed was conducted.

The computation involed a primary step for computing deformations under an external load.

The deformed shape of the Si-membrane and the magnetic layer is used by the Magnetic Field step (it is not necessary to be included in the Electric field step). The model is similar, involving a circular magnetic plate deposited on an elastic membrane (made of Si). Since the magnetic plate position needs to change with fluid pressure, the magnetic plate has been attached to a flexible membrane, hermetically sealed to a support through a rigid frame (Fig.7).

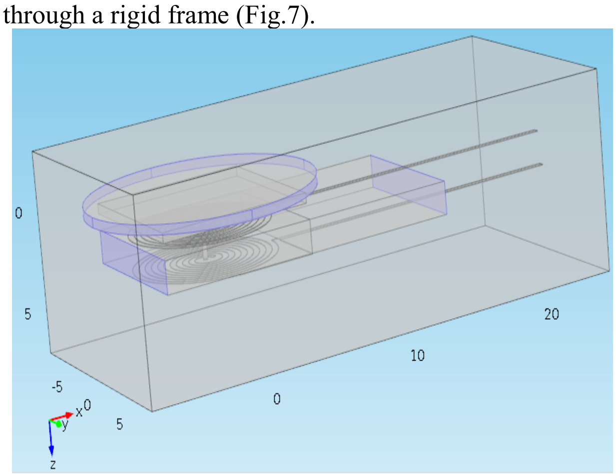

Figure 7. The model with deformable magnetic layer.

MEMS low pressure pneumatic transducers are often used in medical applications, where the measurement ranges usually vary between 5 and 50 kPa [8], as it's the case of equipment used to deliver oxygen to patients. Therefore, the flexible membrane has been dimensioned to obtain displacements in the sensor measuring range (0.1 – 0.8 mm) for a pressure interval between 5– 50 kPa.

A fixed constrained has been applied to the membrane edge, in order to simulate a rigid frame that the membrane is attached to. The sensor assembly will be placed in a rigid enclosure attached to the membrane's rigid frame, in order to protect the sensing elements from the air flow, but the enclosure has not been represented in the sensor design in order to avoid overloading the model. The magnetic plate has been attached to the center of the membrane, the area where the displacements are the largest. The magnetic plate thickness has been set to 0.5 mm and the initial distance between the magnetic plate and the coil has been considered 0.8 mm, the maximum value in the sensor measuring range. A pressure boundary load has been applied to the upper membrane surface, with a value ranging between 5 and 50 kPa, with a step of 0.5 kPa. The whole model has been enclosed in an air domain, used for the delimitation of the magnetic field lines.

Two physics have been used for the computation of this model: Solid Mechanics, used to define the boundary load, the fixed constraints and to calculate the magnetic plate position after the pressure induces a deformation of the membrane and Magnetic and Electric Fields, to calculate the coil inductance and define the magnetization of the mobile plate. Two stationary studies have been run in order to create the numerical model: the first step is calculating the magnetic plate displacement under the action of the boundary load and the second one is calculating the coil inductance.

The mobile plate displacement under the action of pressure applied to the membrane is plotted in Fig. 8. As the input pressure increases, the magnetic plate moves closer to the coil, causing a decrease of inductance. The results are validated by Figure 8, that shows an increase in inductance with the distance between the magnetic plate and the coil. Using a larger mobile plate would most likely yield more accurate results and a wider range of measurement, but increasing the device dimensions would eventually defeat the purpose of a MEMS sensor. The inductance variation has an order of magnitude processable with current electronics and has a cvasi-linear variation in relation to the external applied pressure.

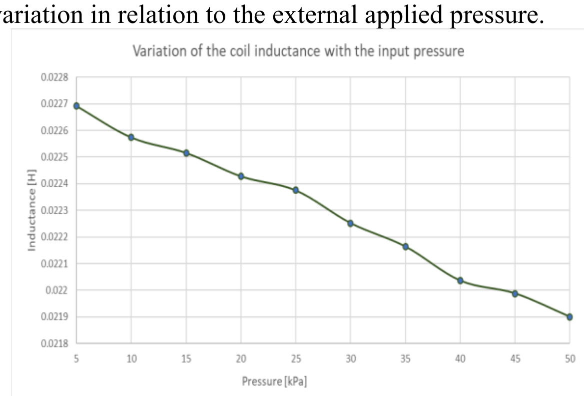

Figure 8. Variation of the coil inductance with applied pressure.

3 Conclusions

The main objective of the paper consists of redesigning a MEMS electrodynamic actuator as a MEMS pressure sensor. Upon studying the actuator's behavior, it was concluded that the device also exhibits sensorial properties, therefore a new functioning principle has been developed and analysed. The concept has been validated by using numerical models and finite element analysis. A new design of MEMS electromagnetic pressure sensor has been proposed and its behavior has been studied and demonstrated through numerical computation. The paper also presents the possibility of optimizing the sensor construction for a wider range of measurements, therefore drawing the directions of future research.

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