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SIMULATION OF MAGNETOELASTIC SENSOR MAGNETIC FIELD DISTRIBUTION IN 3D ENVIRINMENTAL

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The article deals with magnetic field solution in ferromagnetic sensor´s core and simulation of its distribution. The field is solved in both cases, when the external pressure force is and is not affecting the sensor. The mathematical apparatus for field solution is based upon Maxwell´s equations. Magnetoelastic sensors belong to the group of nonlinear systems. They are based upon Villari´s effect. The sensor is connected as a transformator, of which output voltage is proportional to force affecting it. The output voltage of sensor is proportional to change of permeability which leads to magnetic field deformation. For this magnetic field deformation analysis the 3D model of magnetoelastic sensor was created. The sensor´s core is created from feromagnetic material, the solution of magnetic field leads to secondary problem, which is the solution vector magnetic potential in nonlinear environment. The method of finite elements in COSMOS/EMS program was used to calculate the calculate the field describing parameters.

Key words: simulation, magnetoelastic sensor, 3D model, finite element method, ferromagnetic material.

МОДЕЛЮВАННЯ МАГНІТОЕЛАСТИЧНИХ ДАТЧИКІВ РОЗПОДІЛЕННЯ МАГНІТНОГО ПОЛЯ У ТРИВИМІРНОМУ СЕРЕДОВИЩІ

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Розглядається питання розв'язання магнітних полів у феромагнітному середовищі датчика та моделювання його розподілення. Поля розв'язано для двох випадків: коли зовнішня сила тиску впливає й не впливає на датчик. Математичний апарат для розв'язання полів базується на рівняннях Максвела. Магнітоеластичний датчик належить до групи нелінійних систем, які базуються на ефекті Вілларі. Датчик під'єднано до трансформатора, вихідна напруга якого пропорційна силі, що на нього впливає. Вихідна напруга датчика є пропорційною до зміни прохідності, що призводить до деформації магнітного поля. З метою аналізу даного виду деформації магнітного поля було створено тривимірну модель магнітоеластичного датчика. Осердя датчика зроблено з феромагнітного матеріалу, тому розв'язання магнітного поля призводить до вторинної проблеми, а саме до розв'язання векторного магнітного потенціалу в нелінійному середовищі. Для розрахунку описаних параметрів поля було використано метод кінцевих елементів у середовищі COSMOS/EMS.

Ключові слова: моделювання, магнітоеластичний датчик, тривимірна модель, метод кінцевих елементів, феромагнітний матеріал.

INTRODUCTION. One of electrical problems is solution and the modelling of magnetoelastic force sensor followed by simulation of distribution of magnetic field of the sensor [1–6], with which this article deals with.

PROBLEM STATEMENT. One of the basic tasks of the measure technique is sensoring, processing and evaluating of the measured magnitude. As because the solution of many electrotechnic problems by direct experimental examining of physical real system is sometimes quite difficult, it is more convenient to experiment by computer model. Every scientific and technical discipline has its specific issues when composing models. The example can be the modeling of the influence of features of ferromagnetic on the output parameters of elastomatgnetic sensor force. It uses the knowledge of physic of magnetic elements, effect of magnetostriction, features of basic circuits. In this paper we are dealing with elastomagnetic sensor MES-120kN (Fig. 1 and Fig. 2). It is connected like a transformer. The sensor core is made of 50 sheets. The sheets are glued on each other and screwed together. The number of primary turns is 10 and secondary turns is 8 and these parallel windings are placed in four holes. Detailed description of the sensor is in [7]. The inaccuracy of the relation for output sensor voltage in dependence on input force is caused by some simplifications (substitution of non-homogeneous magnetic field by homogeneous circle magnetic field, substitution of non-homogeneous mechanical tension field by the homogeneous one, ignoring mechanical tension concentration around winding hole, ignoring ferromagnetic plates contacts, which transmit pressure to sensor, ignoring defects of supply power (the feeding harmonic current is not constant, it is changed by changing of sensor impedance), small differences in values B, μ (different places in ferromagnetic rolled-section). The main advantages of elastomagnetic sensors are high sensitivity (depending on sensor corematerial), sufficient output voltage and output power, very high reliability, mechanical toughness, ability of multiple force overloading, time-invariant properties (in comparison with strain gauges), and relatively simple construction. One of the sensor shortcomings is difficulty to obtain the formula of exact conversion of output sensor voltage into measured force. Other shortcomings of elastomagnetic sensors are power consumption, ambiguity of transfer characteristic and sensor errors, e.g. non-linearity and hysteresis. At present, the requirements for accuracy and reliability of sensor measuring systems are getting higher. Measuring of massive pressure forces via elastomagnetic sensor is more progressive and reliable than measuring via strain gauges.

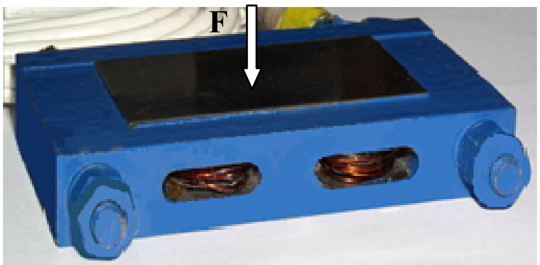

Figure 1 – Magnetoelastic force sensor 120 kN

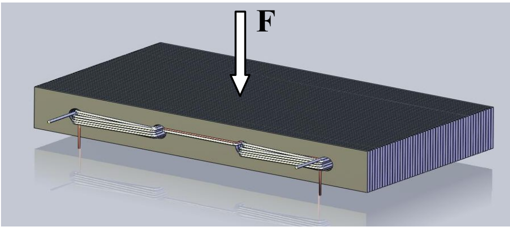

Figure 2 – Design of whole magnetoelastic sensor 120 kN

Previous researches analysis. The elastomagnetic sensor of a pressure force that utilizes the Villary´s phenomena principle, which consists of the fact that if a ferromagnetic body is subjected to mechanical stress, its form is changed and consequently its permeability is changed, too [1]. Villary´s principle is based on equation:

$$\left(\frac{\partial M}{\partial p}\right)_{H,\vartheta} = \left(\frac{\partial w}{\partial H}\right)_{p,\vartheta}, \tag{1}$$

where M is magnetic polarization, p is general pressure, w is relative deformation, H is intensity of magnetic field, ϑ is ambient temperature.

Next relation describes dependency between magnetic induction and magnetic intensity:

$$B = (\mu + \Delta\mu) H, \tag{2}$$

where $\Delta\mu$ represents the increment of permeability caused by acting of external pressure force. The next relation can be obtained by comparing of increments of magnetic and elastomagnetic energies:

$$\frac{1}{2}\Delta\mu H^2 = \sigma\lambda_m, \tag{3}$$

where λ_m represents a magnetostriction coefficient. It is defined like:

$$\lambda_m = \frac{3}{2}\lambda_s \frac{M^2}{M_s^2}. \tag{4}$$

It generally holds that:

$$\frac{M}{M_s} = \frac{B}{B_s}. \tag{5}$$

By utilizing of the last two equations we can obtain the final dependence for permeability increment caused by the acting of external pressure force [8]:

$$\Delta\mu = 3\frac{\sigma\lambda_s\mu^2}{B_s^2}. \tag{6}$$

Since the permeability determines the magnetic field in a ferromagnetic core, so the magnetic field is also changed and we could measure its changes by changes of the induced electric voltage. Properties of the ferromagnetic material have a significant influence on sensor sensitivity, mainly: saturation magnetostriction coefficient λ_s, *p*ermeability of material μ and saturation intrinsic induction B_s .

EXPERIMENTAL PART AND RESULTS OBTAINED. The mathematical model of elastomagnetic sensor is defined in a Cartesian coordinate system (x,y,z*)*.

Partial equation for potential of stationary magnetic field. Derived from Maxwell's differential equations and from definition relations for potentials of stationary magnetic fields at regular points can be equivalent partial differential equation for vector potential.

$$rot\ \mathbf{H} = \mathbf{J}; \tag{7}$$

$$div\ \mathbf{B} = 0, \tag{8}$$

and material equation is

$$\mathbf{B} = \mu\mathbf{H}, \tag{9}$$

where, $\mathbf{H}$ is the magnetic field intensity, $\mathbf{J}$ is the current density, $\mathbf{B}$ is the magnetic flux density, and μ is the material's magnetic permeability. Since *div* **B** = 0, there exists a magnetic vector potential $\mathbf{A}$ such that

$$\mathbf{B} = rot\ \mathbf{A}, \tag{10}$$

and

$$rot\left(\frac{1}{\mu} rot\ \mathbf{A}\right) = \mathbf{J}. \tag{11}$$

For the plane case we assume that the current flows are parallel to the *z*- axis, it means that

$$\mathbf{J} = \mathbf{k}\,A, \tag{12}$$

so only the z component of $\mathbf{A}$ is present

$$\mathbf{A} = \mathbf{k}\,A. \tag{13}$$

And the equation (11) we can simplify to the scalar elliptic Partial Differential Equation (PDE)

$$-div\left(\frac{1}{\mu} grad\ A\right) = J, \tag{14}$$

where

$$J = J(x, y). \tag{15}$$

For the plane case, the magnetic flux density **B** can be computed as

$$\mathbf{B} = \mathbf{i}\frac{\partial A}{\partial y} + \mathbf{j}\left(-\frac{\partial A}{\partial x}\right). \quad (16)$$

And the magnetic field intensity **H** is

$$\mathbf{H} = \frac{1}{\mu}\mathbf{B}. \quad (17)$$

Definition of areas. Area Ω consist of 3 sub-areas (Fig. 3):

Sub-area Ω_1, cross-section of wires of primary winding;

Sub-area Ω_2, air gap between wire windings and lamella;

Sub-area Ω_3, one quarter of lamella's space from ferromagnetic material (possible because of lamella's symmetry).

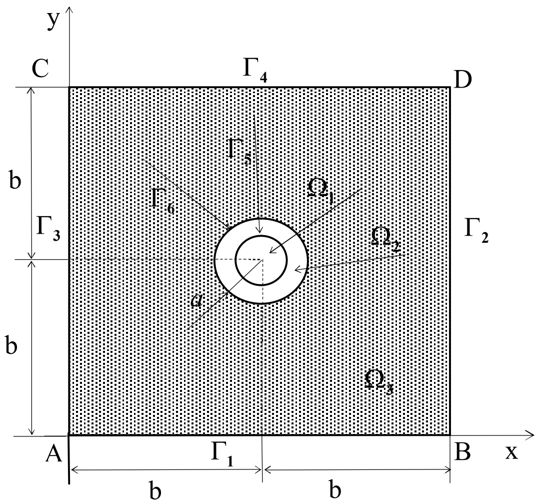

Figure 3 – Definition area of mathematical model of elastomagnetic sensor

Partial Differential Equation coefficients

For determination magnetic vector potential is used the equation (14) which has in each subdomain the following forms:

– in the subdominant Ω_1:

$$\frac{\partial^2 A_{(1)}}{\partial x^2} + \frac{\partial^2 A_{(1)}}{\partial y^2} = -\mu_{(1)} J_{(1)}, \quad (18)$$

where $\mu_{(1)} = \mu_0$ and $J_{(1)} = 1{,}039379.10^7$ Am^{-2},

– in the subdominant Ω_2:

$$\frac{\partial^2 A_{(2)}}{\partial x^2} + \frac{\partial^2 A_{(2)}}{\partial y^2} = -\mu_{(2)} J_{(2)}, \quad (19)$$

where $\mu_{(2)} = \mu_0$ and $J_{(2)} = 0$ A/m^2,

– in the subdominant Ω_3:

$$-\left[\frac{\partial}{\partial x}\left(\frac{1}{\mu_{(3)}}\frac{\partial A_{(3)}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu_{(3)}}\frac{\partial A_{(3)}}{\partial y}\right)\right] = J_{(3)}, \quad (20)$$

and $\mu_{(3)} = \mu_{(3)}(B)$, $J_{(3)} = 0$ A/m^2, so for the vectorial magnetic potential we must use non-linear differential equation.

Boundary conditions. The boundary conditions are:

– on the boundaries Γ_1, Γ_2, Γ_3, Γ_4,

$$A_{(3)} = 0, \quad (21)$$

– on the boundary Γ_5 between subdomain Ω_3 and Ω_2:

$$\frac{1}{\mu_{(3)}}\frac{\partial A_{(3)}}{\partial n} = \frac{1}{\mu_{(2)}}\frac{\partial A_{(2)}}{\partial n}, \quad (22)$$

– on the boundary Γ_6 between subdomain Ω_2 and Ω_1:

$$\frac{\partial A_{(2)}}{\partial n} = \frac{\partial A_{(1)}}{\partial n}. \quad (23)$$

Magnetoelastic sensor's magnetic field solution. Preparation of calculation models consist of three basic stages:

– creation of geometric model;
– definition of physical properties of individual parts of the model;
– generating the network of final elements;
– definition of border conditions.

For magnetic field solution the simplified 3D model (Fig. 4) from sensor's core and primary winding of the coils was created. The task was solved as a magnetostatic problem for chosen value of current in nonlinear environment in the cases when sensor is and is not affected by external force. For magnetostatic analysis sake, magnetization characteristics of chosen material had to be measured. The values measurement for magnetization characteristics was dome by Epstein´s device for frequencies f =400 Hz. From the measured and calculated values graphical dependencie $\mu = f(B)$, (Fig. 5). Because the selected environment doesn´t allow the chaining of mechanical and magnetic fields, the magnetization characteristics had to be recalculated for each frequency using the equation (6) and put into the block.

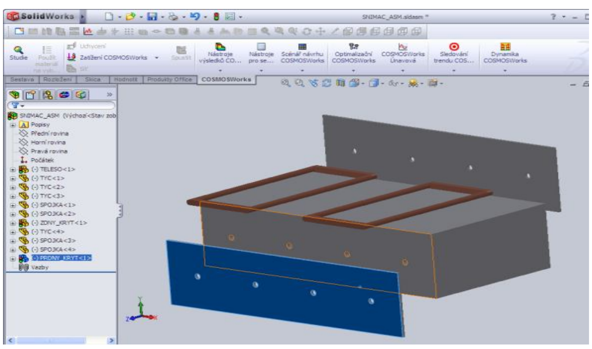

Figure 4 – Simplified geometric model MES

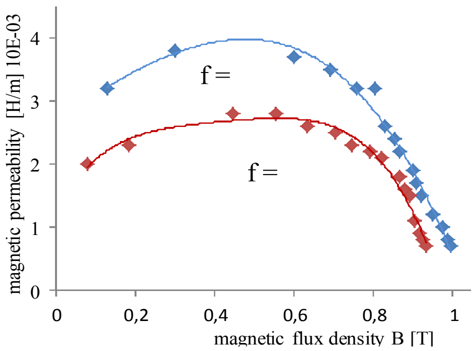

Figure 5 – The dependence of the permeability on the magnetic flux density $\mu = f(B)$

Analysis of magnetic field was realized using the method of finite elements in COSMOS/EMS program. The flowchart of COSMOS/EMS simulation cycle is presented in the Fig. 6.

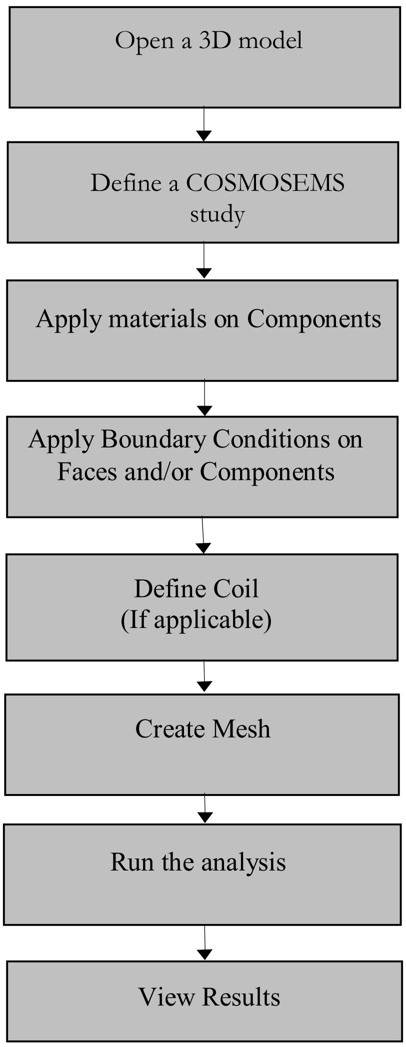

Figure 6 – COSMOS/EMS simulation flowchart

By simulation of model we obtained the pool of output values of magnetic induction B and magnetic field intensity H for feeding current density $J = 1{,}039379.10^7$ $\mathrm{Am^{-2}}$ with frequency 200 Hz and 400 Hz. For each value of current and frequency the external pressure force F was changed to 0 kN, 20 kN, 60 kN, 80 kN, 100 kN and 120 kN.

From the simulation results is clear that when the external pressure force is affecting the sensor´s ferromagnetic core, the field gets deformed and core´s magnetic properties are subject to change which leads to change of magnetic permeability. With increasing force the magnetic inductance value is decreasing (Fig. 7–Fig. 12).

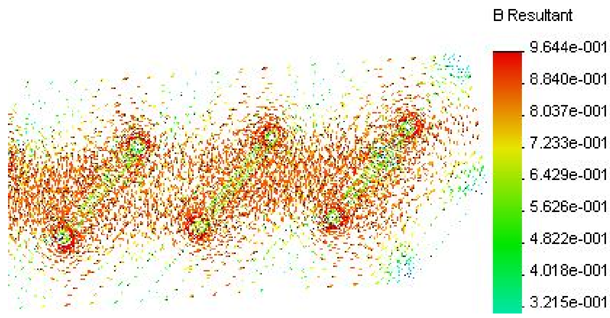

Figure 7 – Distribution of magnetic flux density vector in the dependence on pressure force applied to the sensor, F = 0 kN

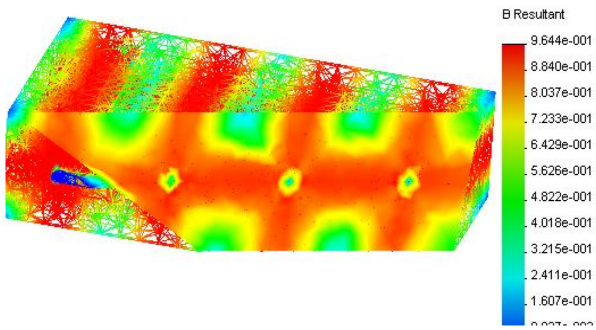

Figure 8 – Distribution of magnetic flux density in the dependence on pressure force applied to the sensor, F = 0 kN

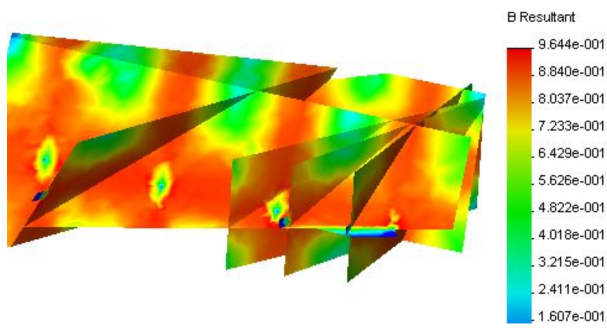

Figure 9 – Distribution of magnetic flux density in the dependence on pressure force applied to the sensor, (section 6), F = 0 kN

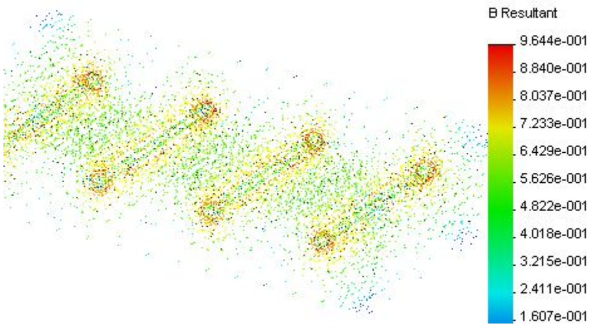

Figure 10 – Distribution of magnetic flux density vector in the dependence on pressure force applied to the sensor, F = 120kN

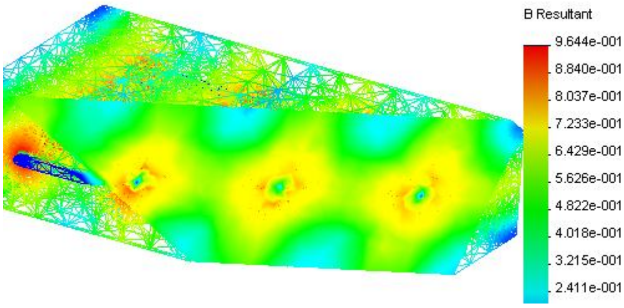

Figure 11 – Distribution of magnetic flux density in the dependence on pressure force applied to the sensor, F = 120 kN

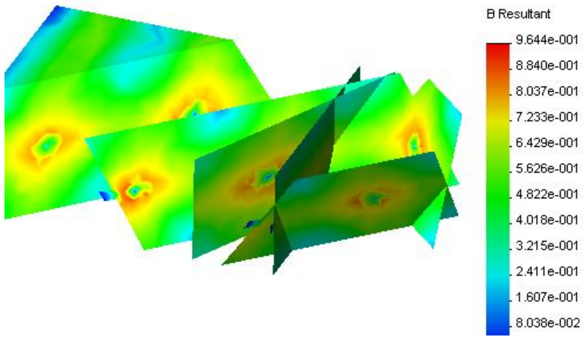

Figure 12 – Distribution of magnetic flux density in the dependence on pressure force applied to the sensor, (section 6), F = 0 kN

The output values of the magnetic intensity of the magnetic field (Fig. 13–Fig. 16).

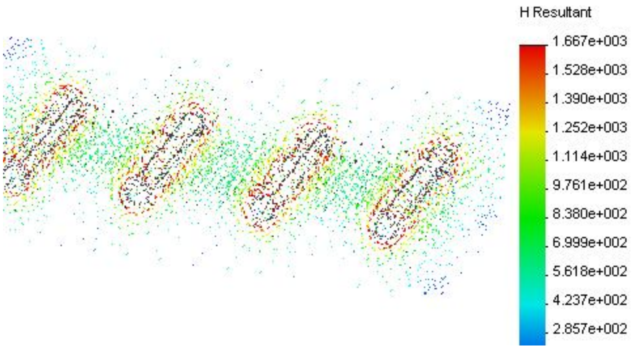

Figure 13 – Distribution of magnetic intenzity vector in the dependence on pressure force applied to the sensor, F = 0 kN

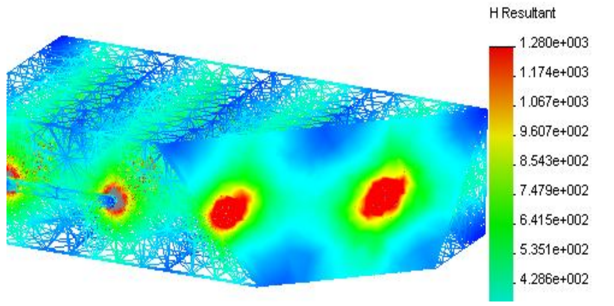

Figure 14 – Distribution of magnetic intensity in the dependence on pressure force applied to the sensor, F = 0 kN

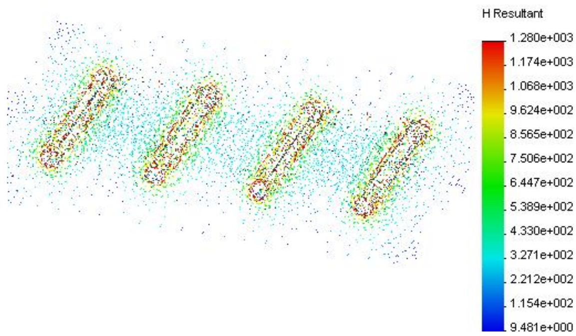

Figure 15 – Distribution of magnetic intensity vector in the dependence on pressure force applied to the sensor, F = 120 kN

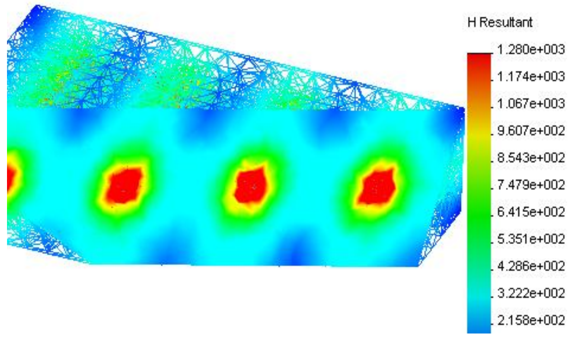

Figure 16 – Distribution of magnetic intensity in the dependence on pressure force applied to the sensor, F = 120 kN

On Fig. 17–Fig. 20 the development of magnetic inductance value dependent on frequency at feeding current 1A is pictured. From the graphs we can see, that with increased value of frequency the magnetic inductance is decreasing.

CONCLUSION. In this article the magnetic field of the elastomagnetic pressure force sensor had been solved. It was solved if the sensor is or is not under the effect of pressure force. From the graphs and progress we can see, that when pressure force is affecting the sensor, the value of magnetic induction decreases rapidly, so the magnetic field gets deformed. This deformation is mostly in sub-areas Ω_2 a Ω_3. Program COSMOS/EMS was used for the calculations, which is based on application of method of finite elements. This program consists of calculation and graphic tools.

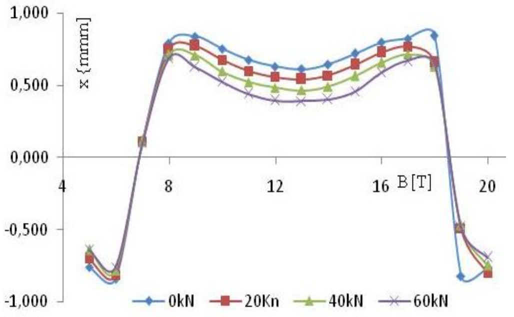

Figure 17 – The dependencies of magnetic flux density, in the dependence on pressure force applied to the sensor, F = 0, 20, 40, 60 kN, f = 400 Hz

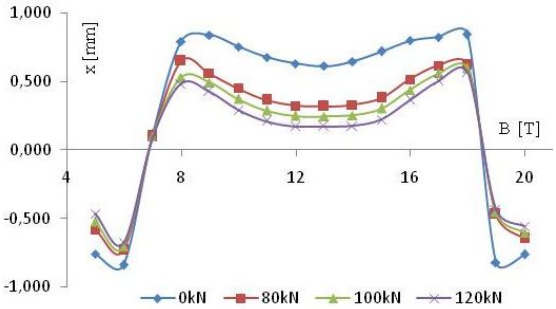

Figure 18 – The dependencies of magnetic flux density, in the dependence on pressure force applied to the sensor, F = 0, 80, 100, 120 kN, f = 400 Hz

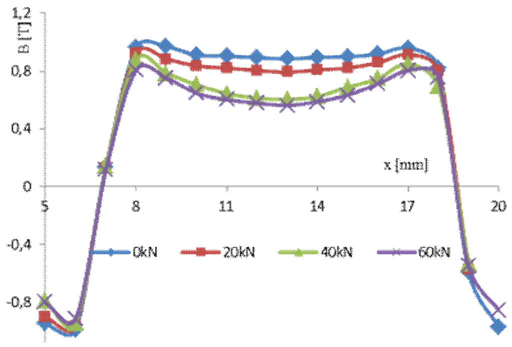

Figure 19 – The dependencies of magnetic flux density, in the dependence on pressure force applied to the sensor, F = 0, 20, 40, 60 kN, f = 200 Hz

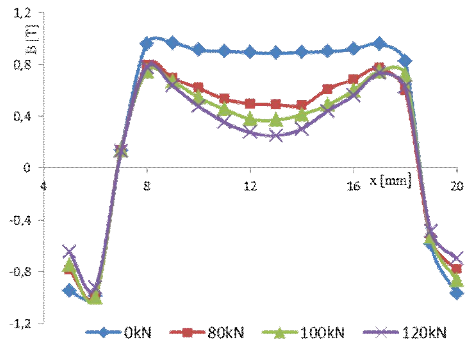

Figure 20 – The dependencies of magnetic flux density, in the dependence on pressure force applied to the sensor, F = 0, 80, 100, 120 kN, f = 20 Hz

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МОДЕЛИРОВАНИЕ МАГНИТОЭЛАСТИЧНЫХ ДАТЧИКОВ РАСПРЕДЕЛЕНИЯ МАГНИТНОГО ПОЛЯ В ТРЕХМЕРНОЙ СРЕДЕ

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Рассматривается вопрос решения магнитных полей в ферромагнитной среде датчика и моделирование его распределения. Поля решены для двух случаев: когда внешняя сила давления влияет и не влияет на датчик. Математический аппарат для решения полей базируется на уравнениях Максвелла. Магнитоэластичный датчик относится к группе нелинейных систем, базирующихся на эффекте Виллари. Датчик подключен к трансформатору, выходное напряжение которого пропорционально силе, которая на него влияет. Выходное напряжение датчика пропорционально изменению проходимости, приводящей к деформации магнитного поля. С целью анализа данного вида деформации магнитного поля была создана трехмерная модель магнитоэластичного датчика. Сердечник датчика сделан из ферромагнитного материала, поэтому решение магнитного поля приводит к вторичной проблеме, а именно к решению векторного магнитного потенциала в нелинейной среде. Для расчета описанных параметров поля был использован метод конечных элементов в среде COSMOS/EMS.

Ключевые слова: моделирование, магнитоэластичный датчик, трехмерная модель, метод конечных элементов, ферромагнитный материал.

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