Bogusław BUTRYŁO

Bialystok University of Technology, Faculty of Electrical Engineering
ORCID: 0000-0002-8835-4756

doi:10.15199/48.2025.03.62

Operating conditions of periodic coil systems in the case of deformation of the magnetic layer

***Abstract**. This paper considers magnetic phenomena in a system of periodically spaced planar coils. The coil system is covered with a deformable layer of material with weak magnetic permeability. The effects of deformation (deflection) of the membrane, the deflection area, on changes in the inductance values of the coils have been evaluated. The aim of the work is to determine the conditions for building a system to identify the surface deformation using a set of planar coils.*

***Streszczenie.** W artykule rozpatrzono zjawiska magnetyczne, rozkład pola i zmiany indukcyjności, w układzie periodycznie rozmieszczonych cewek planarnych. W układzie nad warstwą cewek występuje odkształcalna, elastyczna warstwa materiału (membrana) o słabej przenikalności magnetycznej. W pracy określono wpływ głębokości odkształcenia (ugięcia) membrany oraz obszaru ugięcia na zmiany wartości indukcyjności cewek. Celem badań jest określenie warunków budowy systemu do identyfikacji deformacji powierzchni za pomocą zestawu cewek planarnych. (**Warunki pracy periodycznego układu cewek planarnych w przypadku deformacji warstwy magnetycznej**)*

Keywords: planar structures, periodic coils, magnetic field, flexible magnetic material, numerical modelling.
Słowa kluczowe: układy planarne, periodyczne cewki indukcyjne, pole magnetyczne, elastyczne materiały magnetyczne, metody numeryczne.

Introduction

Elements whose operation is based on the use of magnetic phenomena play an important role in the development of new technologies, and their field of application is wide. The miniaturization of inductive elements, implementation of planar circuits or 3D structures, and the use of new materials allow creation of specific components [1, 2]. The design of planar electrical circuits based on a periodic structure aims to adapt circuit geometries to specific applications related to the development of electronic technologies. Examples of such applications include sensors with distributed sensing area, components for medical applications, soft bodies robots, circuits for wireless power transfer, and energy harvesting [3, 4, 5, 6].

The distributed, planar geometry of the circuit, with periodic structure of components, allows creation the systems where additional factors shape the resultant properties. The design of such components imposes additional requirements, but makes it possible to create systems with qualitatively new features, unusual properties, parameters [2, 5], e.g.:

- a scalable structure of electric elements with adjusted modules arrangement and selected area of operation;
- flexible, deformable structure (geometry) of the resultant circuit, adjusted to the geometry of outer body;
- multi-frequency systems by including (in the periodic structure) components of different design, parameters;
- systems with increased robustness, reliability against damage, due to built-in redundancy. Acceptable, possible damage of parts of the components leading only to limited deterioration of functional characteristics.

The subject of this work is to consider the systems involving periodic planar coil arrangements, a planar inductive displacement sensor composed of a regular two-dimensional array of planar coils. The use of planar system with distributed coils makes it possible to create sensor with detection area, to detect local deformation of the outer surface. The functional characteristics of the system result from the use of a flexible material, a layer (membrane) with soft magnetic properties. Its local, multipoint or surface deformation shapes local magnetic field in the sensor. The paper considers the effect of layer deformation on the parameters of planar coils, due to the possibility of identifying the location, the area of deformation. The paper considers the magnetic phenomena within an elastic magnetorheological (MR) layer with some specific magnetic properties. Changes in coil parameters due to deformation of the MR layer were analysed numerically using the finite element method.

Inductive elements with flexible layer

The design of inductive sensors with flexible layers, including magneto-rheological materials, is the subject of many articles. Planar inductive sensors have been the subject of work for many years, and they find technical and medical applications [7, 8]. An example of single-axis displacement (pressure) sensor design is presented in [9], while triaxis force (displacement) sensor is considered in [10]. Deformation of selected system components (membrane) leads to changing resultant, measurable electrical parameters of the coil (Fig. 1).

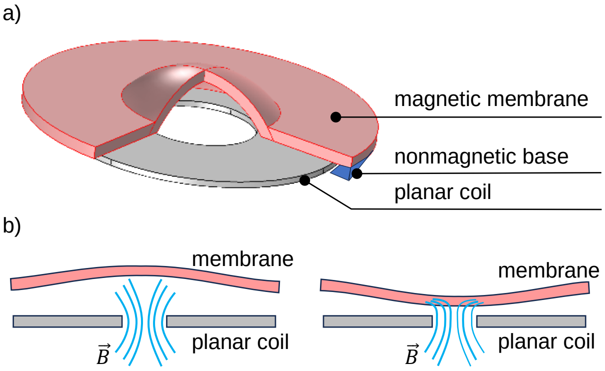

Fig. 1. (a) Typical sensor configuration, main operating element, with single coil. (b) Working principle of the sensor with a flexible membrane of magnetic material: *left* – lower resultant inductance of the coil, *right* – higher inductance [9]

The potential capabilities of the elements, and adaptation to some requirements are closely related to the configurations of coils and applied materials. Work in this area goes beyond the use of ferromagnetic or ferrite elements (layers). Advances in sensor design have resulted from the use of composites, polymer-based deformable, plastic magnetic materials [11, 12, 13]. Magneto-rheological elastomers (MRE), classified as intelligent multi-functional materials (IMFM), are also being used in the design of inductive systems for deformation, force, pressure identification and measurements. The mechanical properties (e.g. elasticity, strength, ductility, fracture toughness) and magnetic properties (permeability, magnetic remanence) of these materials are derived from the base, matrix polymer and actually doped ferromagnetic particles [14, 15, 16]. As a base (matrix) material are usually used: PDMS (polydimethylsiloxane), Ecofex (platinum-catalyzed silicones), PVA (polyvinyl alcohol), Kepton (polyimide, i.e. polyimide films) [17]. The use of different dopants (micrometer-sized powders and fibres) allows to shape the magnetic properties. Relative permeability μ_r of these flexible, deformable materials takes on typical values from 1 to ~10. Depending on the type and concentration of dopants, it is possible to obtain a material with larger value of relative permeability, but mechanical properties become worse. The use of materials with weak magnetic properties ($\mu_r \approx 1.8$) makes it possible to create systems where shaping, deformation of magnetic field can be partially exploited.

Problem formulation

The subject of the analysis is a system composed of a set of periodically ordered planar coils (Fig. 2). The basic coils configurations are: serial, triangular, quadrilateral, etc. The periodicity of the arrangement makes it possible to distinguish some sets of geometrical symmetry axes: $A_{a,i}$, $A_{b,i}$, $A_{c,i}$ (where i - axis index). Depending on the size of the structure, deformation (bending) of coils surface, adaptation to the outer geometry, is possible.

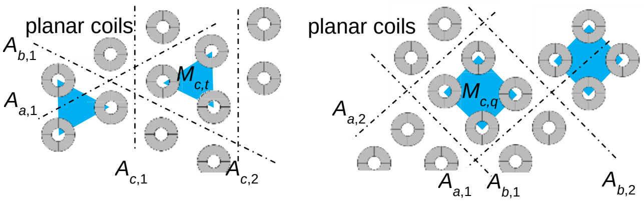

Fig. 2. Basic periodic planar coil configurations: *left* – structure with triangular module ($M_{c,t}$), *right* – structure with quadrilateral module ($M_{c,q}$)

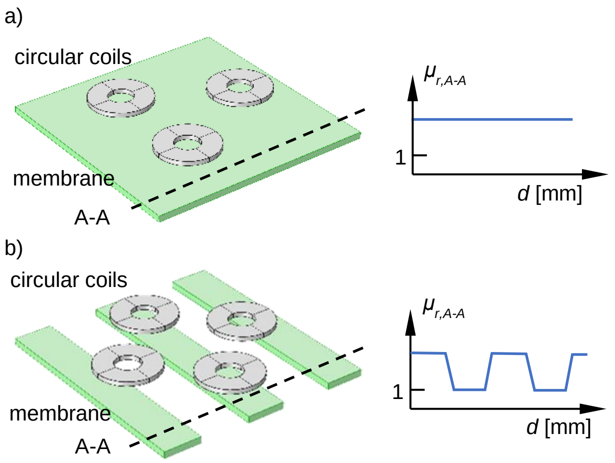

Fig. 3. Sample configurations, view of one module: (a) the triangular configuration of coils ($M_{c,t}$) and the uniform MRE layer; (b) the quadrilateral structure of coils ($M_{c,q}$) and adjusted permeability profile of the MRE membrane

The analysed structure is the set of coils with a flexible surface, distributed magnetic circuit. The surface (membrane) made of MRE is placed above the set of sensors. The key parameters of the structure are highly dependent on the properties of the membrane (magnetic permeability, elasticity). In a typical configuration, the membrane has fixed parameters (Fig. 3a). It is also possible to introduce a material with a specific, selected magnetic permeability profile (Fig. 3b).

The distribution of the magnetic field in the considered system is described by the Ampere-Maxwell equation

$$\text{rot}\left(\frac{1}{\mu_0\mu_r}\vec{B}\right) + (j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)\vec{A} = \vec{J}_s, \tag{1}$$

where $\vec{A}$ is the magnetic vector potential (of course defined assuming Coulomb gauge), ω is the angular frequency of the field source (currents in the coils), $\vec{J}_s$ – the density of external, imposed currents.

The analysed structure is based on the triangular configuration. The calculation included the analysis of a single $M_{c,t}$ module, assuming open space boundary conditions. The interaction of neighbouring, distant modules $M_{c,t}$ was neglected. The membrane has a constant value of magnetic permeability (Fig. 3a). The parameters describing the system (coils and membrane) are summarized in Table 1.

Table 1. Parameters of the analysed configuration

Parameter	Symbol	Unit	Value
Coil: outer radius	r_{out}	mm	8
Coil: inner radius	r_{in}	mm	2.5
Coil: area of upper (lower) surface	S_c	mm²	~2010
Coil: number of turns	n	–	260
Coil: wire diameter	d_w	mm	0.018
Coil: frequency of excitation	f	kHz	2.4
Coil: planar configuration	$M_{c,t}$	–	triangular
Coil: distance between coils	d_c	mm	20
Membrane: width	m_h	mm	2
Membrane: area of deformation (assuming circular shape of deformation)	S_m	mm²	~{80, 500, 1300, 2400, 3400}
Membrane: relative permeability	$\mu_{r,1}$	–	1.84 [9]
	$\mu_{r,2}$	–	4.56

Results

A local deformation of the membrane with weak magnetic properties leads to a local change in the magnetic field distribution within the coil. An example of the field distributions in two adjacent coils is shown in Fig. 4. The local change in the flux linked (when the membrane is deformed, deflected) changes the resultant impedance value of the coil. The location of the deformation and the depth of the local deflection of the membrane (distance to the coil) can be determined from a set of results, measurements from individual coils. For this purpose, the local coil impedance values require further numerical analysis, using some machine learning algorithms.

In order to quantitatively assess the effect of deformation of the magnetic layer (membrane), a coil inductance variation factor was adopted

$$w_L(x, y, d) = \frac{L_{c,d} - L_{c,0}}{L_{c,0}} \cdot 100\%, \tag{2}$$

where $L_{c,d} = f(x_d, y_d, d)$ is the inductance of the coil at a given deflection of the membrane, $L_{c,0}$ – the inductance of the coil in the base version (membrane in the no-load state), d – the local distance between coil and membrane. Due to the variation of the coil inductance value from position (x_d, y_d) and deflection value (distance d), the coefficient w_L has be determined locally (for a given coil).

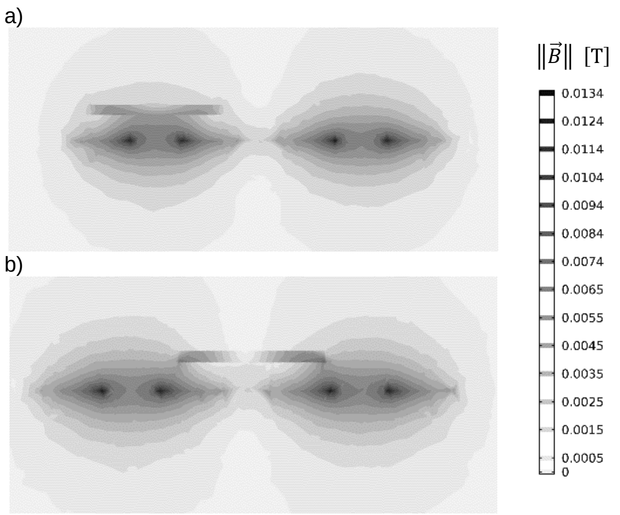

Fig. 4. Some examples magnetic field distributions in the coils and membrane (vertical cross-section): (a) the membrane is placed over the left coil, (b) the membrane is between two coils. 2D view in the plane of geometrical symmetry of the two coils (results of simulation using the finite element method)

The deformation of the magnetic layer (membrane) depends on the properties of the elastomer. Due to the possibilities, detection targets, the area of the deformation is also important. Therefore, different sizes of the area of the membrane deformation (close-up of the membrane to the coil) are taken into account. The relative value of the deformation area is stated by equation

$$a = \frac{S_m}{S_c}, \quad (3)$$

where S_m is the area of the local membrane deformation (assuming circular shape of the deformation), S_c – the area of the planar coil (surface parallel to the membrane). The values of S_m and S_c are summarized in Table 1. The sizes of the deformation area for the subsequent variants are {0.04, 0.25, 0.64, 1.21, 1.69} respectively.

The results of the analyses of the successive variants, assuming that the value of the magnetic permeability of the membrane is $\mu_{r,2}$ = 4.56, are shown in Figs. 5 and 6. The results presented show that at deflection of d = 2 mm, the relative inductance changes w_L are in the range of (7%, 26%), in the case when deflection is above the coil. If the deflection is between two coils, the inductance changes range is (3%, 11%). The changes given are for the case when the deformation area is equal or comparable to the geometrical size of the coil, a = {1.21, 1.69}. Significant changes in w_L coefficient are also observed when the deformation area is smaller than the coil area (a = 0.64), but the allowable, detectable deflection of the membrane is smaller. The comparison of the results in Figs. 5 and 6 shows that the deformation of a layer with a relatively small area (a = {0.04, 0.25}) is not detectable. Changes in the inductance coefficient w_L are small, below the assumed level.

The usability of the system requires selection of the geometry of the coils, configuration and spacing between the elements. An important factor and constraint of the analysis, is the membrane properties. The Fig. 7 summarises the results of the analyses for two materials with different values of magnetic permeability (Table 1). The results obtained confirm that decreasing the value of magnetic permeability decreases the value of inductance changes. The changes in the value of inductance reach up to 8%. Both systems can be used for deflection d = 1.5 mm. A partial improvement, correcting the parameters, can be achieved by selecting other coil configurations (number, diameter and distance between coils).

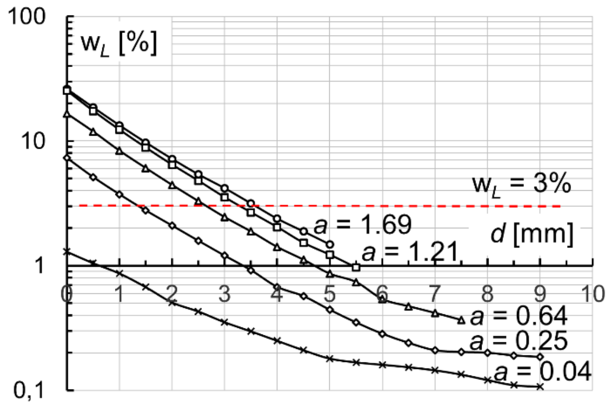

Fig. 5. Changes in inductance coeffcient w_L with deformation (deflection) of the membrane directly above the coil (d - local distance coil- membrane)

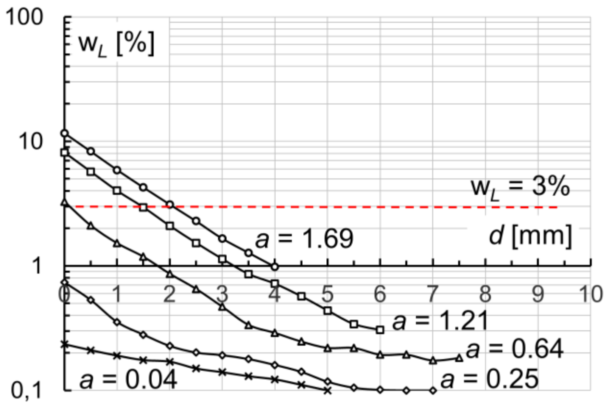

Fig. 6. Changes in inductance coeffcient w_L with deformation (deflection) of the membrane in the area between two coils (d - local coil-membrane distance)

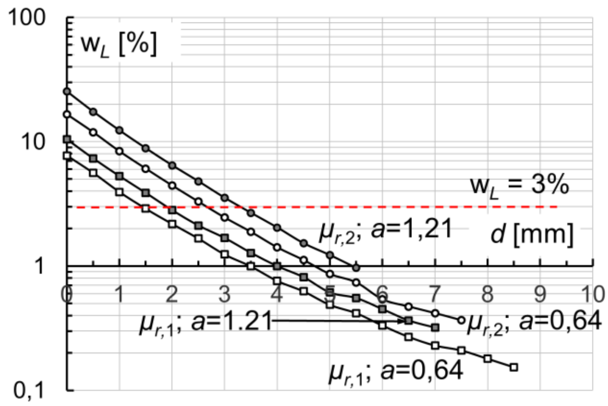

Fig. 7. Comparison of inductance coeffcient w_L considering two values of membrane permeability (Table 1). Deflection of the membrane is centrally above the coil

Conclusions

A configuration consisting of the periodic planar coil array and the distributed planar magnetic circuit with weak magnetic properties was considered. The presented system can be scaled, adjusted by changing the parameters of the coils, the distance between the coils, the geometry of the periodic array, and the properties of the membrane.

The analysed system allows detection of the area and depth of deflection of the membrane layer. It is therefore possible to take into account the deflection of the layer due to external factors. The surface of the system does not have to be rigid as with other types of sensors.

Calculations carried out indicate that, with a surface deformation of up to d = 2 mm, changes in inductance of at least 3% are achieved. The changes in inductance and the associated shape change detection strictly depend on the area of the deformation surface in relation to the size of the coil. For small, point-like deformations, changes in the inductance values of the system remain small, impossible to take into account in the identification process. The presented analysis results can be used to train an artificial intelligence system to detect the surface area and interaction force for a given coil configuration.

This work was supported by the Ministry of Science and Higher Education in Poland at the Białystok University of Technology under research subsidy no. WZ/WE-IA/7/2023.

***Authors**: Assoc. Prof. Bogusław Butryło, DSc PhD Eng., Białystok University of Technology, Faculty of Electrical Engineering, Wiejska 45D, 15-351 Białystok, e-mail: b.butrylo@pb.edu.pl.*

REFERENCES

[1] Zazoum B., Batoo K. M., Ali Khan M. A., Recent advances in flexible sensors and their applications, *Sensors*, 22 (2022), no. 12, paper no. 4653
[2] Pan L., Xie Y., Yang H., Li M., Bao X., Shang J., Li R.-W., Flexible magnetic sensors, *Sensors*, 23 (2023), no. 8, paper no. 4083
[3] Li Y., Grabham N., Torah R., Tudor J., Beeby S., Textile-based flexible coils for wireless inductive power transmission, *Applied Sciences*, 8 (2018), no. 6, paper no. 912
[4] Zhang J., Chen G., Jin Z., Chen J., A review on magnetic smart skin as human–machine interfaces, *Advanced Electronic Materials*, 10 (2024), paper no. 2300677
[5] Sheng P., Wang B., Li R., Flexible magnetic thin films and devices, *Journal of Semiconductors*, 39 (2018), no. 1, paper no. 011006
[6] Xu X., Liu W., Zhao Z., Huang Y., Zhu T., Efficient magnetic shielding by designing layered composite with nanocrystalline and permalloy for weak magnetic measurement, *Sensors & Actuators: A. Physical*, 375 (2023), paper no. 115538
[7] Chiu Y., Chen Y. Z., Hsieh C. C., Hon H. C., Design and characterization of a flexible relative pressure sensor with embedded micro pressure channel fabricated by flexible Printed Circuit Board technology, *IEEE Sensors Journal*, 21 (2021), no. 24, pp. 27343 – 27351
[8] Dias dos Reis D., Castaldo F. C., Pichorim S. F., Flexible circuits for moisture measurement in cylindrical timber of wood, *IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)*, July 2019, United Kingdom
[9] Wang H., Totaro M., Blandin A. A., Beccai L., A wireless inductive sensing technology for soft pneumatic actuators using magnetorheological elasomers, *2nd IEEE International Conference on Soft Robotics (RoboSoft)*, April 2019, pp. 242–248, Seoul, Korea
[10] Kawasetsu T., Horii T., Ishihara H., Asada M., Flexible tri-axis tactile sensor using spiral inductor and magnetorheological elastomer, *IEEE Sensors Journal*, 18 (2018), pp. 5834-5841
[11] Vatandoost H., Sedaghati R., Rakheja S., A novel methodology for accurate estimation of magnetic permeability of magnetorheological elastomers, *Journal of Magnetism and Magnetic Materials*, 560 (2022), paper no. 169669
[12] Weir G., Leveneur J., Long N., Magnetic susceptibility of soft magnetic composite materials, *Journal of Magnetism and Magnetic Materials*, 551 (2022), paper no. 169103
[13] Ziaja J., Jaroszewski M., Lewandowski M., Sasuła M., Flexible materials used in electromagnetic field shielding (in Polish), *Przegląd Elektrotechniczny*, 94 (2018), no. 10, pp. 73-76
[14] Romeis D., Saphiannikova M., Effective magnetic susceptibility in magnetoactive composites, *Journal of Magnetism and Magnetic Materials*, 565 (2023), paper no. 170197
[15] Trompetter B., Leveneur J., Goddard-Winchester M., Rumsey B., Turner J., Weir G., et al., Ferrite based soft magnetic composite development intended for inroad charging application, *Journal of Magnetism and Magnetic Materials*, 570 (2023), paper no. 170530
[16] Sołtys K., Bartel S., Kluszczyński K., Laboratory method of producing ferromagnetic powders and flexible magnetic materials and experimental studies of their behaviour in a 3D electromagnetic chamber (in Polish), *Przegląd Elektrotechniczny*, 99 (2023), no. 7, pp. 169-175
[17] Shen H., Gao B., Pan S., Liu L., Yang G., Flexible magnetic film: key technologies and applications, *Journal of Magnetism and Magnetic Materials*, 587 (2023), paper no. 171310