Lukas MARSALKA

Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology, Institute of Electrical Engineering

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Electromagnetic field properties influence by the changes of dielectric material constant

***Abstract**. This paper deals with of input parameters observation of the electromagnetic field generator. The frequency course character of this parameter plays a key role in specific sensor kind sensing principle. This senor is designed for non-electrical quantities measurement. The sensing principle is based on changes of electromagnetic field properties which are affected by this sensor resonance. This paper contains complete design of this sensor with analytical model, which describe sensing principle. The second part of this paper is focused to detail numerical analysis by new multi-numerical calculation techniques. Result of this analysis describe not only the sensor functionality but also change of sensor characteristic when is used structural material with another dielectric parameters.*

***Streszczenie.** Artykuł dotyczy analizy parametrów wejściowych generatora pola elektromagnetycznego. Charakterystyki częstotliwościowe tych parametrów odgrywają kluczową rolę w zastosowaniu specyficznego czujnika. Czujnik ten został zaprojektowany do pomiaru wielkości nieelektrycznych. Zasada działania bazuje na zmianach właściwości pola elektromagnetycznego przy zmianach częstotliwości rezonansowej czujnika. Artykuł opisuje cały proces projektowania czujnika łącznie z modelem analitycznym opisującym zasadę działania. Druga część artykułu skupia się na analizie numerycznej wykorzystującej hybrydowe metody obliczeniowe. Wyniki analizy pokazują zastosowanie czujnika wykonanego z różnych materiałów o różnych parametrach dielektrycznych. (**Zmiany właściwości pola elektromagnetycznego w zależności od stałej dielektrycznej materiału**).*

Keywords: mutual impedance, numerical calculation; resonance circuit; sensor, method of moments.
Słowa kluczowe: impedancja wzajemna; obliczenia numeryczne; obwód rezonansowy; czujnik; metoda momentów.

Introduction

Nowadays is technical word characteristic with precipitous technological application developments, which help power the quality of live. This fact leads to specific technical area improve such as sensor technic. Following this fact is created solid tone to new electrical and non-electrical sensor development too. The measurement problem is created mainly in case of non-electrical sensing in unusual environment. These environments are characteristic with high temperature, ferromagnetic material sensibility, micrometric dimensions etc.

For example, in medical area, the MRI device does not allow any ferromagnetic material within its vicinity. In micrometric area are classical sensors sensitive to others (undesirable) quantities what causes large measurement error in sensing process. For example, the dimensions of the tensometers have to be less than measured micro object dimensions and in micrometers, or for some applications in nanometers. These strain-gauge dimensions are influenced with light and gas sensitivity, etc. which is not convenient for these applications. Another complication is in the data transfer between external control unit and micro object, where it is impossible to realize the transfer of the measured value with help of wires. This restriction is dependent on micro object construction, mainly on dimensions and propositions between the micro object and signal wires. In case when the signal wires are used for data transfer the micro object structure can lose mobility or have restricted functions and usability.

The new sensor category is development for application in these harsh environments. This kind of sensor is called as the hybrid sensor [2]. The main idea rest in two or more different sensing principle, they are integrated to the one sensing element. This new sensing principle using leads to negative properties elimination and needs properties reinforcing.

Basically this, a new kind of hybrid sensor for force sensing is development. This sensor makes use of changes electromagnetic field properties changes with combination of load cell technology. Electromagnetic field problematic is one of the more important physical areas, which is using in many technical spheres. Today it is applied to communication, data transferring, detection of position, and for physical quantities measurement too [3], [4], [5].

The load cell technology is very popular technology in matter of force investigating and measuring. As a technology for force sensing, load cell is attractive also because of the fact, that underlying technology are relatively mature and well known. Load cell technology is applied to indirect measurement techniques for measurement physical quantities such as torque sensor application, stability sensor application, water level sensor application, etc.

Mutual combination of these technologies may leads to creation of new category hybrid sensor, which will by suitable for measurement application in mentioned harsh environment. However is necessary a number of simulation and laboratory measurement realized. This is very important for hidden defects detection, which may create between these two measurement technologies.

This paper introduced the basic sensing principle of proposed sensor, moreover is in the paper describe the designed model of force sensor for numerical simulation. The numerical simulation pointed to dependence of resonance effect. This effect is influencing not only value of sensing quantities, but also with the dielectric constant of material from who is created load cell.

Sensing principle of designed hybrid sensor

Before we focus to specific problematic it is necessary describe the sensing physical background of designed sensor. Let as consider an electromagnetic field, which is generated by a simple wire structure, for example half-wave dipole (wire 1). Put another dipole, with the same dimensions as wire 1, into the vicinity of the wire 1, as is shown on Fig. 1.

During the interaction, these two dipoles are influencing each other. This influence causes generation of the mutual impedance between dipole 1 and dipole 2. The mutual interaction between wire 1 and wire 2 is possible to describe by mathematical formula for mutual impedance:

$$\dot{Z}_{21} = -\frac{2}{\dot{I}_{2k}} \int_{-l_2/2}^{l_2/2} \dot{\mathrm{E}}_{z12}(z)\dot{I}_{z2}(z)dz \tag{1}$$

where: $\dot{E}_{z12}(z)$ - tangential part of EM field intensity at the point z_2; $\dot{I}_{z2}(z)$ - current distribution across wire 2; $\dot{I}_{2k}$ - the maximal current value on the input terminals of wire 2.

The Input parameter – input impedance of wire structure Z_1 is possible to express by simple mathematical formula (2). This formula describes contribution of mentioned mutual effect to the input parameter of wire 1.

(2) $$\dot{Z}_1 = \dot{Z}_{11} + \dot{Z}_{21}$$

where: $\dot{Z}_{11}$ – self impedance of wire 1

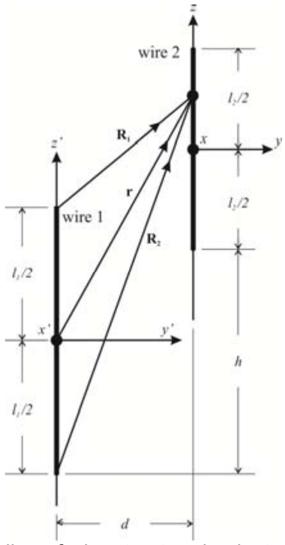

Fig. 1. Mutual coupling of wire structure in electromagnetic field.

The solid line graph (Fig.2) indicates the frequency course of wire structure input impedance in dependence on the length of wire 2. This length change can causes the different frequency position of the local minimum. According to [6], this phenomenon is given by resonance of wire 2 let while the value of this resonance is corresponding to the length of wire 2. By using this mutual effect there is possible to directly measure the length or on the other hand to indirectly measure others quantities like force and et cetera.

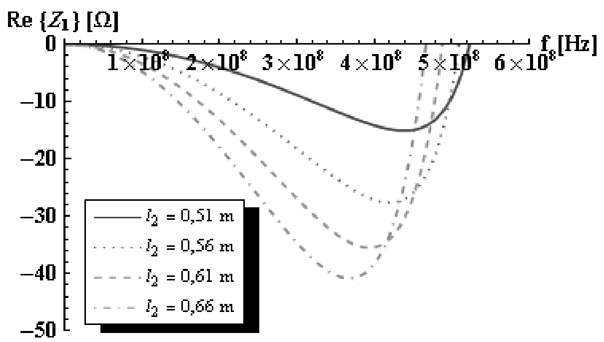

Fig. 2. Wire structure input impedance as a function length of wire 2, analytical model calculated by Inducted EMF method.

Sensor numerical model

The direct implementation of wire structure (Fig.1) is impossible in area of force sensing. Due this fact it is necessary to replace the wires by more convenient elements to force sensing. Our proposed solution is illustrated at the figure 3.

The wire 1 is replaced by EM radiator with more convenient (linear) input frequency characteristic. The linear course of characteristic is key to be capable to observe the resonance effect more precisely. This kind of EM field radiator is usually knows as stripline [7].

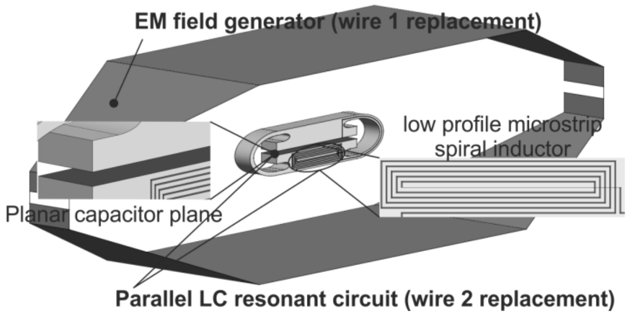

Fig. 3. Complete designed model of sensor for numerical calculation.

The possible replacement of resonance element (wire 2) can be created by parallel resonance LC circuit as we can see at the figure 3. The main problem still remains to be the technical realization of the inductor. Because of the position of load cell implementation and measurements of this position there was low profile micro strip spiral inductor chosen. The capacitor or more precisely the capacitor plates are created by silver layer on elastic body planar part.

The final designed shape of proposed load cell with full load is shown in figure 4. Let us focus to the part of elastic body, where is only negligible deformation influence. This part plays an important role in the application part of resonance circuit – inductor. Design and numerical simulation of elastic body was executed by simulation software Multiphysic Comsol [8].

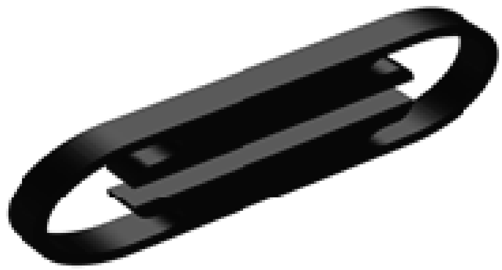

Fig. 4. Designed mechanical part shape – load cell of pressure sensor.

The sensor resonance frequency is tuned directly to corresponding elastic body deformation. The change of resonance frequency is dependent only to the capacity of the capacitor in this case. Other parameters of resonance circuits are constant during the whole sensing process. The value of capacitor capacity is given only to the mutual distance of capacitor plates d (0 < d < 1,5 mm). The inverse proportionality is between the capacitor plate distance and sensing value of force. Specific equivalent materials of modelled sensor structure are stated in Table 1.

Table 1. Buildings materials of designed sensor

Used materials:	Structure parts:
Brass (σ=2.5647 S.m^{-1})	Stripline - EM field generator
Silver (σ=6.1737 S.m^{-1})	LC resonator
Teflon (ε_r=2.08 F.m^{-1}), Nylon (ε_r=5.00 F.m^{-1}), Pertinax (ε_r= 10.00 F.m^{-1})	Load cell – designed sensor mechanical part

Multi-numerical techniques in FEKO environment

A detailed numerical analysis in electromagnetic area is very important to resonance effect investigation of designed sensor. The majority of structures of electromagnetic interest contain regions of non-metallic materials. In our case it is the mechanical part of sensor – load cell. The applicability of a numerical analysis tool is greatly reduced by incapability of limitation in treating dielectric regions.

While it is possible to use a single numerical technique to solve such problems, it is often advantageous to solve different parts with different techniques best suited for these parts, and then combining these together into one solution within a hybrid framework. These hybrid methods, which can combine the advantages of two of more different numerical techniques, have been developed to analyse complex problems consisting from metallic and dielectric parts of arbitrary shape that cannot be resolved conveniently, and accurately, by using them individually.

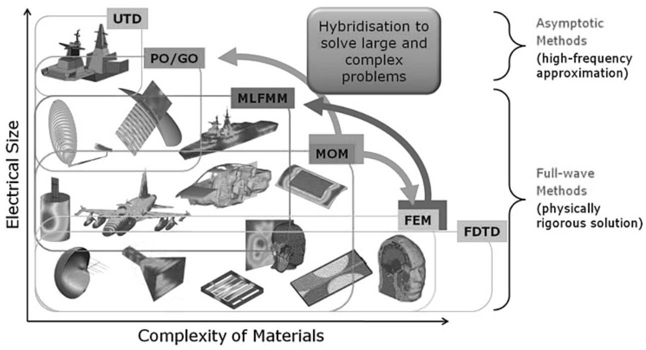

Fig. 5. A complex EM problems numerical modelling by FEKO software.

FEM/MoM hybrid technique utilizes the two techniques in the region of the problem to which they are best suited (Fig.5.). It is a rigorous solution, meaning that all electromagnetic interactions are taken into account. Typically, an inhomogeneous region with rapidly varying dielectric constant is modeled inside of an enclosed space. The MoM is then used in the region external to the medium, and the FEM is used inside of the FEM region. An additional boundary condition, to ensure field continuity, is applied to both techniques on the boundary surface. This gives the advantages of the MoM in the MoM region, as well as the advantages of FEM in the FEM region [9].

Results of numerical calculation

As was mentioned, the sensing principle is based on resonance frequency change of sensor's electrical part, which is dependent on distance between capacitor's plates, which are implemented on specific part of load cell. During the sensing process specific parts of load cell (where plates of capacitor are implemented) are changed. As it was mentioned before, the behaviour of the wire structure at the resonant frequency is similar to those of resonant circuits. Therefore, it is necessary to analyse influences of such a resonant circuit on the strapline's input characteristics. We consider the scattering parameter s_{11} for our case.

Because of our designed sensor structure specific properties such as dimensions of particular parts and types of applied materials, the hybrid numerical technique was chosen. The dielectric part of sensor structure (load cell) was calculated by FEM technique and conducting parts of sensor structure were calculated by MoM technique.

The selected frequency courses of stripline reflection coefficient are illustrated at solid line graph (Fig. 6). The resonance effect is very clear in the aspect of frequency position of the local minimum in this case too.

The relation of resonance effect in dependence on kind of employed dielectric material was investigated in the next numerical calculation. The frequency position of local minimum (resonance effect) in dependence on type of dielectric material is illustrated on following chart (Fig. 7). The observable affection of position of local minimum by dielectric material type is clearly visible. This dependence is caused by change of resonance circuit parameter due to the dielectric material permittivity. This phenomenon is very important at the point of sensor transfer characteristic constriction.

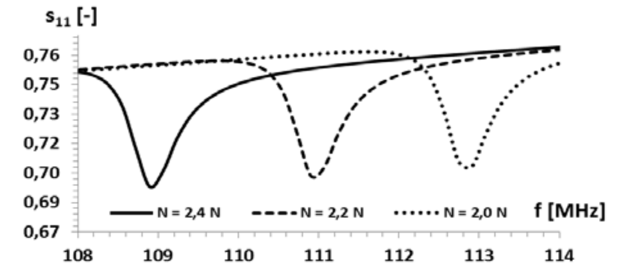

Fig. 6. Resonance effect on the stripline input port in dependence on value of sensing force.

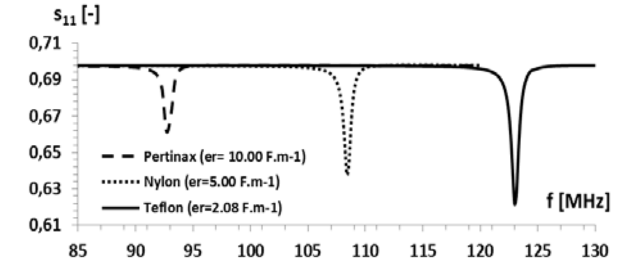

Fig. 7. Resonance effect on the stripline input port in dependence on value of dielectric material properties (constant sensing force).

Conclusion

The presented paper is primarily dealing with design model and numerical implementation of hybrid sensor applicable to force measurement. The numerical calculation results of modelled structure confirm the input parameter sensitivity of stripline. The simulation of designed structure demonstrates that the simulation software FEKO is suitable for calculation in sensing area, when the model is predetermined within numerical techniques condition. The detailed numerical analysis confirms the validity and functionality of our presented theory. The described principles of force measurements appear to be very perspective and useful also for other non-electrical quantities like length, vibration, pressure and so on.

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***Authors**: Ing. Lukas Marsalka, PhD. Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology, Institute of Electrical Engineering, Ilkovicova 3, 812 19 Bratislava, Slovakia, E-mail: lukas.marsalka@stuba.sk*

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