Comprehensive Numerical Analysis of Designed Force Sensor Based on Changes of Electromagnetic Field Properties

L. Marsalka, R. Hartansky, V. Smiesko

Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Electrical Engineering, Bratislava, Slovakia
Email: lukas.marsalka@stuba.sk

Abstract. *This paper deals with force sensor design applicable to measure the forces up to 10 N. Presented sensor is based on the method which is capable to indirectly measure the forces using deformation of load cell. The resonance circuit frequency is primarily affected by deformation or mutual change of load cell specific parts. The resonation circuit itself together with load cell is understood as one single unit. The resonance effect can create the chance of properties in surrounding EM field. This change is easily recognized by change of EM radiator input parameters variation. Our discussed sensor proposal could be used not only in academic sphere but also could have a practical application.*

Keywords: Pressure Sensor, Load Cell, Electromagnetic Field Properties, Resonance Circuit

Introduction

Nowadays there is an exponential growth of the applications, where the force measurement is a goal. The large amounts of application where these measurements are used impose the requirements for sensor characteristics. Beside the basic characteristics like resolution, range and linearity, there could be material and shape realization characteristics also taken into account. For example, in medical area, the MRI device does not allow any ferromagnetic material within its vicinity. Force sensor is one of the most important sensors in robot force control system. These sensors are used to perceive the contact force between the operator and external environment. In this case the shape of force sensor is also very important due to its implementation to the robotic construction [1].

The load cell technology is very popular 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. The crucial sensing element is a strain gauge, which is difficult to produce in the case of micro meter scale and is not suitable for unsparing treatment.

The main objective of this paper is to focus on the design of mechanical part – elastic body and electrical part – resonance circuit, which together create a force sensor. The design of elastic body shape was oriented to creation of planar parts, which mutual position is changed by value of sensing force. This effect produces a direct influence to the properties of electrical part of designed sensor. Electrical part of sensor – resonance circuit, makes use of resonance effect which takes the information about measured force. This information is propagating in change of electromagnetic (EM) field which surround designed sensor. This change is easily detected at the input terminal of EM field radiator.

Theoretical background of sensing principle

A physical essence of sensing principle is based on mutual interaction of simple wires structure (Fig. 1). Active wires (marked as 1) generate the EM field and therefore the properties of generated EM field are changed by presence of the next wire (marked as 2).

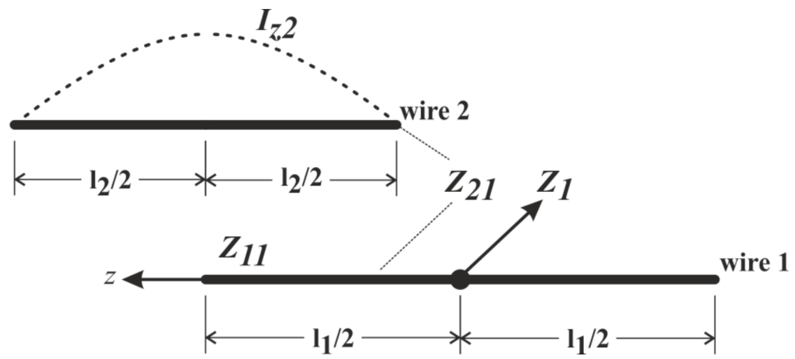


Figure l Mutual coupling of wire structure

The mutual interaction between wire 1 and wire 2 is possible to describe by mathematical formula for mutual impedance:

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

where:

$\dot{E}_{z21}(z')$ –tangential part of EM field intensity at the point z_2
$\dot{I}_2(z')$ – current distribution across wire 2
$\dot{I}_{2k}$ – the maximal current value on the input terminals of wire 2.

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.

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

where:

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

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 [2], 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.

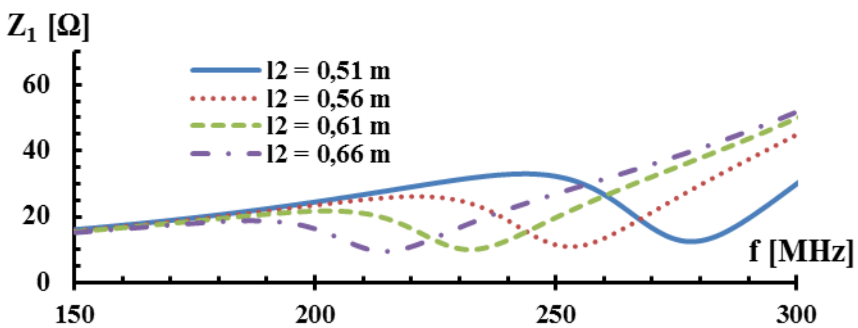
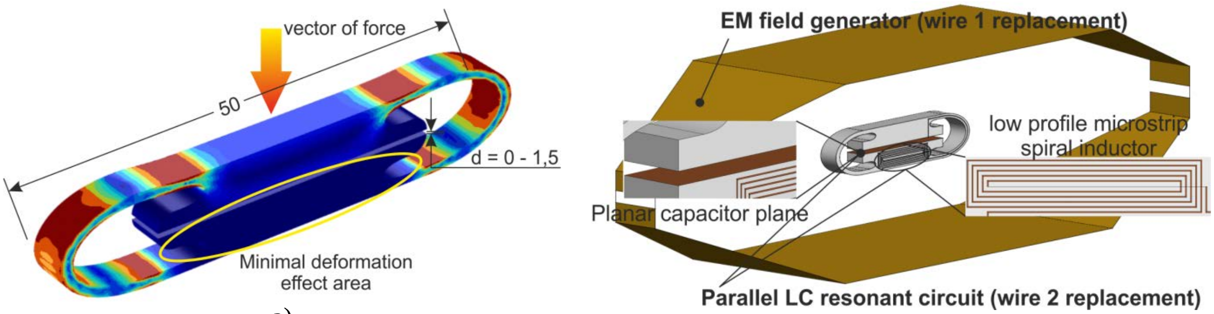


Figure 2 Changes of waving wire structure input impedance as a function length of wire 2

Design of force sensor model for numerical simulation

The final designed shape of proposed elastic body with full load is shown in figure 3. Let us focus to the part of elastic body, where is only negligible deformation influence. This part plays an important role in the application of resonance circuit. Design and numerical simulation of elastic body was executed by simulation software *Multiphysic Comsol* [3].

But 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 3b).



a) b)

Figure 3. a) Designed mechanical part of pressure sensor (full load $d = 0$ *mm*, dimensions in *mm*), b) implementation of electrical and resonance parts

The wire 1 is replaced by EM radiator with constant input frequency characteristic. The constant 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* [4].

The possible replacement of resonance element (wire 2) can be created by parallel resonance LC circuit as we can see at the figure 3b). The main problem still remains to be the technical realization of the inductor. Because of the position of elastic body 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 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.

Results of numerical simulations

A detailed numerical analysis is very important to resonance effect investigation of designed sensor. The numerical *moment method* was used to calculation of EM field changes. Material constants were defined for particular parts of sensor: stripline, inductor – copper, capacitor plates – silver, elastic body – teflon.

The selected frequency courses of stripline input impedance are illustrated at following solid line graph (Fig. 4a). The resonance effect is very clear in the aspect of frequency position of the local minimum in this case too.

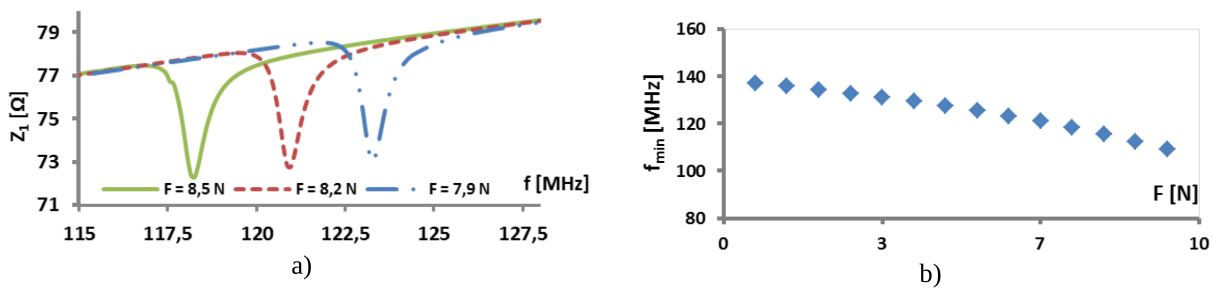


Figure 4. a) resonance effect on the stripline input port, b)transfer curve of sensor obtained by results of numerical simulation

The transfer curve of designed sensor is plotted at the figure 4b. This characteristic was created from results of numerical simulations. The constructed transfer characteristic presents the relationship between sensing value of force and frequency value of resonance effect. This frequency value plays a key role in the next interpretation process.

Conclusions

The presented paper is primarily dealing with design and numerical implementation of force sensor based on the changes of EM field characteristics. These changes are caused and influenced by the shape deformation of our presented load cell structure or more specifically said by the characteristic changes of the most crucial element of sensor - resonance circuit. 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.

Acknowledgements

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