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Wireless passive sensor for crack detection - conception and investigations

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Abstract

This paper presents the concept of a passive, wireless sensor based on RFID technology, used for detecting cracks in ceramic parts, plates and equipment. It describes the conception of project of this kind of a sensor, its principle of operation and possible application. The paper deals with the second stage of investigations on this sensor (simulation and experiments of operating principle, prototypes that check manufacturing possibilities, process of transponder design).

Keywords: wireless sensor, RFID, planar coil designing, SHM, concrete structure, ceramic crack detection.

Bezprzewodowy, pasywny czujnik uszkodzeń powierzchni - koncepcja i badania

Streszczenie

W artykule zaprezentowana została druga część badań nad bezprzewodowym czujnikiem opartym na technologii RFID, służącym do wykrywania uszkodzeń w elementach ceramicznych, używanych w wielu dziedzinach techniki. Koncepcja czujnika opiera się na stworzeniu obwodu rezonansowego składającego się z cewki planarnej, nadrukowanej bezpośrednio na elemencie ceramicznym oraz kondensatora będącego integralną częścią chipu RFID. Pojawiające się uszkodzenie, przerywa ścieżki cewki, co prowadzi do braku sygnału zwrotnego w czytniku dostrojonym do określonej częstotliwości. Tego typu czujnik, ze względu na swoje cechy, takie jak niska cena jednostkowa, możliwość umieszczania w miejscach trudnodostępnych bądź niewidocznych, czy brak własnego źródła zasilania, może znaleźć zastosowanie w różnorakich aplikacjach (monitoring stanu konstrukcji żelbetowych, ułatwiona diagnostyka płytek umieszczanych w kamizelkach kuloodpornych, diagnostyka łożysk ceramicznych). W poniższym referacie zaprezentowane zostały rezultaty kolejnych badań nad czujnikiem tego typu (doświadczalne sprawdzenie zasady działania czujnika na nowej partii prototypów, porównanie otrzymanych wyników z symulacją, planowany proces projektowania nowego transpondera).

Słowa kluczowe: czujnik bezprzewodowy, RFID, projektowanie cewki planarnej, SHM, konstrukcje betonowe, wykrywanie uszkodzeń ceramiki.

1. Introduction

A wireless sensor used for crack detection in ceramic, without its own power source, is a very attractive solution for Structural Health Monitoring (SHM), military and industry. There is a constantly growing demand for this kind of sensors in the mentioned market area. There are admittedly many sensors created for the purpose of crack detection in ceramic and constructions, for instance the CVM sensor described in [2], the fiber optics sensor [3], as well as sensors based on MEMS technology [4]. All of the presented sensors could be used in SHM, however, they have many weaknesses connected with the necessity of being wired or having a battery. The mentioned drawbacks are the reason for this type of sensors not to fit in many applications and thus they are not widely used in SHM tasks.

There are also wireless passive sensors shown in various other researches, but all of those devices are designed for different applications. There is a concept of a sensor, which uses conductively printed pattern on concrete beams or printed sheet on steel beams to detect cracks due to the changes in impedance [5]. The sensor designed by us is more integrated than the aforementioned one. The sensing element belongs directly to a transponder, there are no additional tracks connected outside the sensor. There is also a sensor proposed in [6], whose project is similar to ours, however, there is a significant difference in application of the RFID technology, that allows reading many sensors at the same time, due to the unique tag ID number. Another advantage of our solution is the possibility to direct deposition of the sensor element which is the planar coil on ceramic elements. There are also other RFID-based sensors presented in [7,8], used in e.g. military helicopters, but their principle of operation is based on connection of an additional sensor, as for instance a strain gauge sensor or a light sensor to RFID-tag.

The described sensor has the following principle of operation: it is a threshold sensor, changing its state by the appearance of crack damage. Therefore, the sensor has a form of a simple resonant circuit, connected with the RFID chip. The circuit inductance element is a fully planar coil printed, or applied in another way, directly on the ceramic element. The planar coil size must be adequate to the given element, so that the coil occupies the greatest part of the element surface. There is no layer (e.g. foil) between the sensor susceptible circuit and the element. The capacitance elements are, depending on frequency range of system, additional SMD capacitors or a capacitor integrated with the RFID chip internal circuit. Using the nomenclature of the RFID technology such a system of the coil and capacitance could be called a transponder. The designed sensor system is tuned to the determined resonant frequency (operating frequency), according to the frequency of the standard commercially available. When a crack occurs, tracks, which form the planar coil, are interrupted. There is no more backscattered signal in the RFID reader, thus we can conclude that the ceramic part is damaged. One could prepare database with sensors ID and upload it to the reader's microcontroller and then asses the state of many sensors by interrogation with the reader.

After the analysis of the papers on crack propagation in ceramic elements [9,10], one could conclude that occurring a crack damage surely interrupts the coil track regardless of the crack size, width and the source of damage. On the other hand, the appropriate protection of the coil surface should prevent false alarms due to such clashes of the circuit from the element surface.

As can be seen, the concept of a sensor is trivial, however, it has many advantages comparing to the presented solutions and this feature reflects its innovative character. It has no power source, no wires, it could be read even after twenty years and could be placed in any place (for instance under elevation), there is no need to place it in a visible area.

The possible applications are wireless sensors for crack detection in ceramic plates placed into bulletproof vests, which would allow for significant reduction of the bulletproof vest diagnostic time, special plate specimens with this sensor used in SHM in tasks connected with health monitoring of a concrete structure and in maintenance of machines that contain ceramic elements (for instance ceramic bearings). Thanks to low cost and simple construction, this type of a sensor has great chance to become ubiquity.

The concept of our designed sensor, its principle of operation and first investigations were wider described in the previous paper [11]. In this document, we want to focus on new research on this sensor, including simulations and description of a new transponder design process. This task (designing the new transponder coil) is the most important issue of the project of the RFID system.

2. Description of investigations

There was developed a test method of the entire system, carried out to check the supposed resonance frequency. The main subject of examinations was the S11 parameter of the entire system measured with a standard loop probe (in our case it is ISO 10373-7 standard loop antenna) connected to the network analyzer. By examinations of the S11 parameter in the standard loop probe, we could receive the operating frequency value of the transponder magnetically coupled with the probe, by analyzing the resonance peak location Using this kind of a probe introduces an additional mutual inductance to the system, which causes a slight displacement in occurrence of the resonant peak. Therefore we decided to compare the obtained results with simultaneously prepared simulation of this two-coil system. The prepared simulation environment was similar to examination of this system by the network analyzer in the frequency range, where the resonant peak was supposed to be (10 – 15 MHz). The entire simulation was prepared in PSpice, with the determined value of the mutually coupled inductances. By using this method, we examined a commercial transponder tuned to 13,56 MHz and then our prototypes.

There was manufactured a prototype used for accurate design of a planar coil, with the inductance calculated by the best method proposed in the earlier paper. The way of designing the well-tuned planar coil was described in [12]. The experimental method consists in manufacturing three coils, with inductance equal to the theoretical inductance connected with the assumed operational frequency of 13,56 MHz and inductance larger and smaller by 5%. After the manufacturing process, the added capacitance element (SMD capacitor for instance) tunes the system to the specified frequency. In the final system the role of capacitance plays a fully internal capacitor included in the RFID chip. After examining the resonance peak locus, there was chosen the coil which corresponded best to the model and the entire process was repeated for three coils with lower dispersion of the inductance value (for instance +/- 2%). Use of this method enables receiving a planar coil with excellent matching to the resonant frequency. This method complements the preliminary calculating methods of planar coil inductance. After the prototyping process on PCB, the designed coil is applied on a ceramic surface.

During a new transponder coil design the principle of operation was also experimentally checked. It assumes that occurrence of a crack damage leads to interruption of the track and, thus, changes in the impedance (hence, in the RFID reader tuned to the specified operating frequency there is lack of the backscattered signal).

The crack was introduced to the entire system as interruption in conductive traces of the planar coil (Fig. 1). Afterwards the entire system was examined with the same test parameters and the received results were compared with those obtained from the undamaged system.

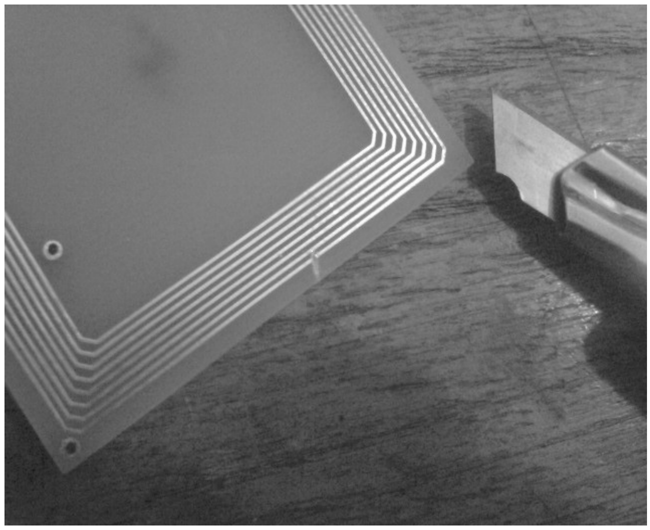

Fig. 1. Prototype coil with introduced damage
Rys. 1. Cewka prototypowa z wprowadzonym uszkodzeniem

3. Results and discussion

By analysing the obtained results we can conclude that the model system of the planar coil belonging to the commercial transponder ANT1-M24LR-A provided by STMicroelectronics has resonance in 13.36 MHz (Fig. 2). The slight displacement of the resonant peak is caused by impact of the additional mutual inductance added by the standard loop probe. This result matched excellent with the PSpice simulation result of the adequate coupled system (Fig. 3). It should be noted that both values of the gain are unimportant in this type of research and could not be compared due to the fact that in experiments we examined the S11 parameter. However, the important information resulting from this study was location of the resonance peak, which demonstrates the value of the operating frequency.

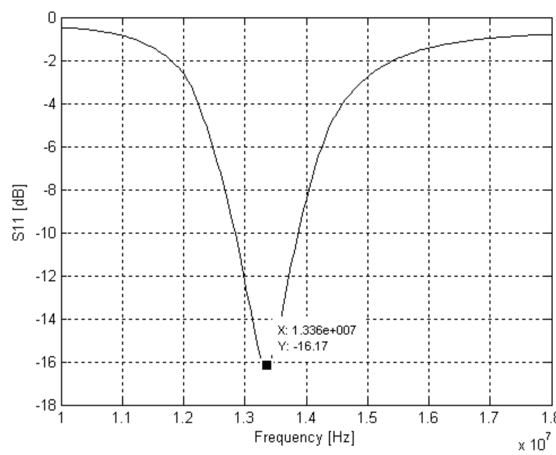

Fig. 2. Resonance peak in commercial 13,56 MHz system - experiment
Rys. 2. Pik rezonansowy dla komercyjnego systemu 13,56 MHz - eksperyment

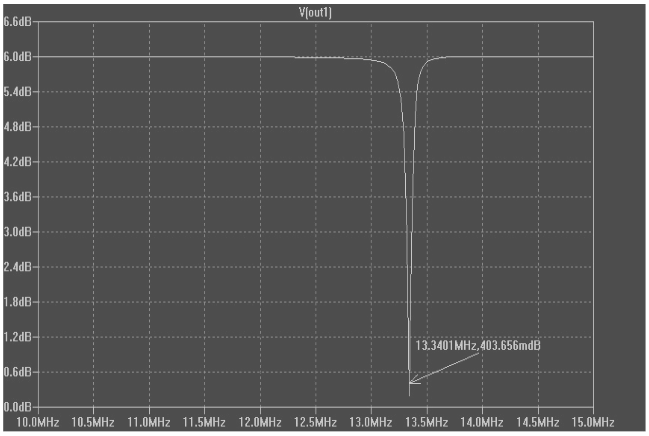

Fig. 3. Resonance peak in commercial 13,56 MHz system - simulation
Rys. 3. Pik rezonansowy dla komercyjnego systemu 13,56 MHz - symulacja

By analysig the results in the cases when the crack occurs, there is clearly visible that the resonance peak is significantly displaced (Fig. 4). It is the most important result of our investigations. By displacement of the resonance peak, there is no more the backscattered signal in the RFID reader, therefore we can conclude that our assumption related to the principle of operation was correct. An important fact is that the signal disappears after a failure of even one turn of the coil. On the other hand, this type of a sensor gives no information about the size and location of a damage. It can provide only information that the coil with a certain ID number is interrupted at least in one place. As far as the resonant frequency is concerned, there is a difference in comparison to the commercial transponder; the resonance peak occurs at the frequency value of about 12,26 MHz. This is due to the incorrect manufacturing process of this prototype, but has no impact on the results during examination of the operating principle.

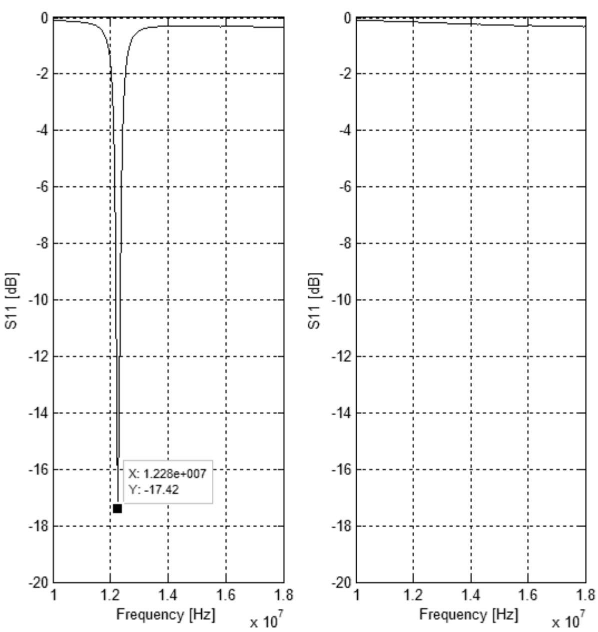

Fig. 4. S11 parameter of the prototype coil before (left) and after (right) damage
Rys. 4. Parametr S11cewki prototypowej przed (lewa) oraz po (prawa) uszkodzeniu

4. Conclusion

In our investigations the principle of operation of the designed sensor was examined. The real impact of the crack damage on changes of the resonant response was checked. The results were compared with those obtained from previous simulations of the described system. The process of the transponder design, adopted for our application, was also described. This next step of research shows the correct way of developing process of the crack damage sensor whose concept was described in the earlier paper.

The next stage of investigations will be a design of the RFID system tuned to 13,56 MHz operating frequency and transfer of this transponder project to manufacturing directly on any ceramic elements. We will also investigate the usefulness of such a system in SHM and maintenance of a bulletproof vest, which is the most significant application area for this sensor. All investigations will be preceded by adequate simulations which allow reducing cost of the design process and better recognition of the system physical properties.

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