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A Feasibility Study for Cracks Detection in Metallic Prosthetic Implants by Radio-Frequency Coils

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Abstract

In this paper we develop a feasibility analysis for non-invasive detection of internal cracks in metallic prosthetic implants by using a radio-frequency magnetic field. The proposed hardware arrangement, operating at 3 MHz, consists in a resonant spiral coil coupled to an unloaded concentric probe loop. The cracks detection can be accomplished by detecting the frequency and amplitude shift of the system input impedance caused by the induced currents on the implant metallic surface. The proposed method can overcome health risks associated with typical follow-up techniques after the surgery such as X-rays, while being less expensive and easily integrable within hospital facilities. The observed results suggest the feasibility of an innovative near-field clinical device, to be employed in future for non-invasive detection and monitoring of prostheses internal cracks, thus encouraging further analysis.

1 Introduction

The use of metallic prosthetic implants is becoming a relatively common and diffused practice in clinical environment [1]. Not only total limb prosthetic devices, but also orthopedic metallic implants are particularly employed to fix and restore serious bone fractures in different body locations (harms, knees, backbone). As a matter of fact, metallic prosthetic implants are raising as an important tool for the quality of life improvement of patients.

Nonetheless, one of the most significant problem for metallic prostheses is the presence of internal cracks or defects caused by the wear of materials or mechanical failure [1]. The presence of these defects may lead to fractures and implants failure, that could be very painful and dangerous for the patient. For that reason, after the surgery procedure, it is necessary to carefully follow-up the patient in order to monitor the implant state.

Currently, there are no specific methods to prevent prostheses failures before they actually occur, and the more common detection way is based upon the pain of the patient. Till now, the typical monitoring technique is by using X-rays. However, the invasiveness of this method for the patient, caused by the use of ionizing radiation with a relatively high dose, has been widely demonstrated. Thus, it is not a surprise if the cracks detection inside metallic prostheses is a topic that raises significant interests in the scientific community.

It may be interesting to point out that the surface cracks detection is an important problem in the industrial field for the testing and monitoring of concrete manufacts and metallic components in order to evaluate their structural stability. In particular, inhomogeneities and fatigue cracks in metals can compromise the industrial products functioning. To avoid this problem, some non-destructive methods have been developed based upon electromagnetic radiation, working at significantly high frequencies [2]. However, high frequency device, operating in the range of GHz, can be relatively expensive and complex to be realized. With a specific reference to biomedical applications, different cracks detection methods have been proposed: wireless sensors directly integrated inside the bone [3], distributed electrodes (forming the so-called Space Filling Curve [4]) and also evanescent microwave probes [5].

Thus, in order to overcome these limits, we conduct in this paper a feasibility study for the detection and monitoring of internal cracks in metallic prosthetic implants, to be performed in a contactless, portable and safe manner. Specifically, we propose a hardware arrangement working at 3 MHz consisting in a resonant spiral coil coupled with an unloaded concentric probe loop. In particular, the aim of this work is to combine simultaneously low operative frequencies with small dimensions, thus conceiving a simple and relatively low-cost future device that can be easily adopted in any hospital facilities and making the follow-up procedure easier.

The paper is organized as follows: in Section 2, we introduce the basic physical concepts behind the proposed approach; Section 3 is devoted to present the coils design and to describe the numerical test-case. Some discussions about the obtained results are derived in Section 4. Finally, Conclusion follow.

2 Methods

As introduced, the proposed innovative detection method consists in an internal resonant spiral coil inductively coupled to a non-resonant concentric active probe loop [6] (Fig. 1). The advantages of this configuration rely on the excellent system frequency selectivity, and, consequently, device sensibility. This can be guaranteed by ensuring a high Q-factor value for the internal resonant spiral coil.

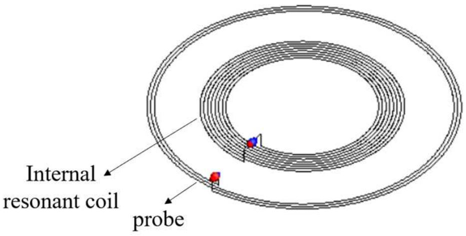

Figure 1. CAD model of the proposed detection system**.**

The detection of presumptive cracks in the metal implant is achieved by observing the frequency and amplitude shifts of the probe loop input impedance. In particular, the input impedance (and, thus, the reflection coefficient) is sensitive to the current distribution changes within the metallic implant, caused by the cracks presence. Indeed, the currents distribution are related to the magnetic flux produced by the radiating system onto the metallic implant, as explained by the Faraday's law:

$$\oint \vec{e} \cdot \vec{\iota}_l dl = -\frac{\partial}{\partial t} \oiint \vec{b} \cdot \vec{\iota n}\, dS \qquad (1)$$

while the currents density is related to the induced electric field by the following expression:

$$\vec{J} = \sigma\vec{e} \qquad (2)$$

Hence, the resonant frequency shift and the different reflection coefficient magnitude can be both used to detect eventual defects or inhomogeneities in metal implants inside human body.

Table 1. CAD dimensions of the proposed detection system.

	Internal Spiral Coil	*External Probe loop*
Radius (mm)	10	20
Number of Turns (N)	8	3

3 Numerical set-up

In order to verify our method, we designed a specific numerical set-up, exploiting an electromagnetic solver based on the Method of Moments (Feko Suite, Altair, Troy, MI, USA).

The conceived radiating arrangement (Fig. 1) was designed to operate at 3 MHz. The two coils of the system are realized with a 0.32 mm radius lossy copper wire, whereas the internal spiral coil was made resonant at the desired frequency with an opportune capacitor. The internal spiral coil has a diameter of 10 mm, while the external probe loop is larger (20 mm diameter). In particular, the system dimensions are summarized in Table 1.

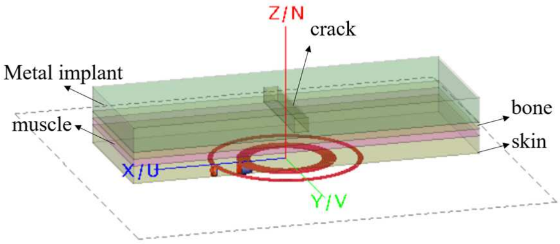

Figure 2. CAD model comprising human tissues, metal implant and crack. The tissues block is placed 2 mm away from the detection system.

To simulate a realistic scenario, we introduced the metallic implant, realized in PEC, inside biological phantom (Fig. 2). The phantom comprises three layers of different tissues: skin, muscle and bone, whose dielectric properties and thicknesses are reported in Table 2 [7]. The distance between the radiating system and the human phantom has been assumed as 2 mm (Fig. 2).

Then, we compared two configurations, i.e., metallic implant with and without the presence of a crack, whose width and depth are both 2 mm, and length is 30 mm. We also investigated the different system response as a function of crack dimensions (i.e., by changing the crack width) (see Fig. 2).

Table 2. Dielectric properties of the human tissues used to realize the biological phantom.

	ε_r	$\sigma\ (\frac{S}{m})$	*Thickness (mm)*
Skin	643.7	0.29	5
Muscle	522.4	0.57	3
Bone	212.9	0.021	4

4 Results

In Fig. 3, we reported the result of the numerical simulation performed on the setup described in Fig. 2 (i.e., with and without the crack in the prothesis). According to the theorical concept, the presence of the defect leads to a significant resonant frequency shift (+150 kHz) and also the reflection coefficient magnitude varies (from -6 to -9 dB).

As explained before, another way to visualize the presence of a crack in the metal implant consists in the input impedance analysis; thus, we used this quantity to investigate different crack dimensions. In particular we change the crack width (x axis). As evident in Fig. 4, the impedance maximum absolute value decreases when the crack dimension is becoming larger.

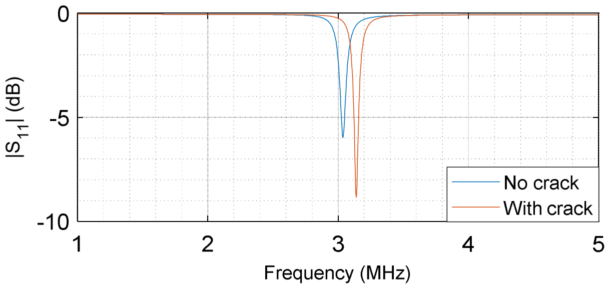

Figure 3. Reflection coefficent absolute value of the system with and without the presence of crack inside the metal implant.

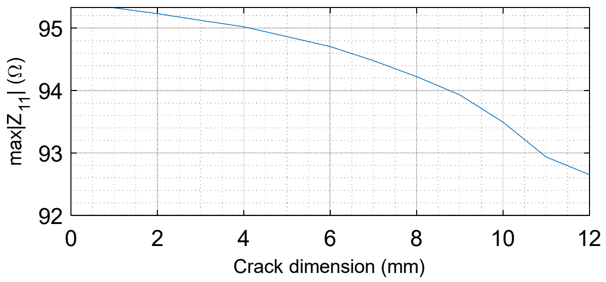

Figure 4. Input impedance maximum absolute value as a function of the crack dimension.

Hence, these preliminary studies validated the theorical approach and they are useful to evaluate, during the crack detection, the severity of the metal prothesis failure as well as to obtain information about the geometrical crack details. Therefore, these results are promising and encourage further analysis.

4 Conclusion

In this paper we developed a feasibility study for the detection of internal cracks in metal prostheses in an innovative, contactless and low-frequency way. We designed through an electromagnetic solver an inner resonant spiral coil inductively coupled with a non-resonant concentric active probe loop, working at 3 MHz. Thanks to the system sensitivity, the detection is possible by simply monitoring the main system parameters; in particular, the presence of the defect changes the currents distribution in the metal surface of the implant, affecting the resonant frequency, the input impedance and the reflection coefficient.

In this work, we also demonstrate the system parameters variation as a function of the crack dimension. In this way, not only the defect presence detection but also the monitoring of the implant failure severity can be accomplished. Overall, the obtained preliminary results confirmed the theoretical approach and encourage future work. Moreover, the proposed method is able to overcome the health risks associated to the X-rays technique typically used for the follow-up after a surgery, making it easier and less expensive.

5 References

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