A novel concept for tissue-metal detection and differentiation using an inductive proximity sensor

A Gorczewska¹, A Poliński¹, J Wtorek¹, B Truyen²

¹Gdansk University of Technology, Faculty of Electronics, Telecommunications and Informatics, ul. Narutowicza 11/12, 80-233 Gdansk, Poland
²Vrije Universiteit Brussel, Faculty of Engineering, Boulevard de la Plaine 2, 1050 Ixelles, Belgium

E-mail: jerzy.wtorek@eti.pg.gda.pl

Abstract. In this paper a novel application of inductive proximity sensors for detection of living tissue by means of measurements of the coil impedance changes at different frequencies is described. The mathematical analyses utilizing Bessel function estimation include detected object size and its distance from a sensor. The main aim of this study is to prove the possibility of distinguishing between metal objects and living tissues. The movement of an object can be also detected, assuming it is in a distance comparable with a size of the induction sensor.

1. Introduction

Proximity sensors are utilized in many applications in the industry, new technologies or home appliances. One of the fields of utilization of proximity sensors is the branch known as the human-system interaction. However, methods that are applied to living tissue detection are not realized only by proximity sensors but involve also other measurement techniques. A brief overview of the existing systems for the living tissue detection, as well as a short introduction to the principles of operation of such methods is presented below.

Typically, the living tissue can be detected by utilization of optical, thermal, ultrasounds, electric or electromagnetic methods. Generally, sensors can be divided due to the range of object detection. When a disturbance occurs close to the sensor the inductance or capacitance sensors are applied. When the distance between them is larger (e.g. in industry applications) it is better to use ultrasounds, photoelectric or radar sensors.

One of the types of sensors, which are able to detect a living tissue, is the ultrasound sensor. It is widely utilized for a diagnostic and treatment purposes of a human tissue. Their different interactions with tissue depend on their types (generally a different velocity of ultrasounds in a medium). Some of the emitted waves reflect, others propagate and partially scatter in a medium. Impact on it has an essential parameter called the acoustic impedance, which is a measure of a medium reaction to the acoustic wave. The unit of the specific acoustic impedance, $Z_a$, is Rayl [$kg \ m^{-2} \ s^{-1}$]. This parameter for living tissue and a metal object differ about an order of magnitude. For an air the acoustic impedance is yet four times smaller than for the living tissue [1]. The ultrasound sensors which are utilized on a large distance (even to 300 m) are applied only to metal object. Thus a transmitted wave is entirely
reflected from the metallic object, which causes a larger difference of the specific acoustic impedance between air and the metal (e.g. aluminium $Z_a=1.7\times10^6$ Rayl, air $Z_a=4\times10^2$ Rayl).

Living tissues are more similar to an air than to metallic materials. They have lower value of reflection coefficient. It is a result of the fact that a boundary between air and soft tissue is not so sharp (difference between acoustic impedance of the air and the tissue is not so big).

Optical measurements of the living tissue are generally led in the regions of the greatest optical transparency, i.e., the tissue optical window (600 to 1300 nm) [2]. This is a range where blood components have the most impact on the absorption coefficient. Utilizing optical methods it is possible to detect and visualize biological tissue with a high-resolution. Due to the scattering of a light the light source-object distance must be short and does not exceed a few centimeters. The same situation concerns such medium as a fabric clothes which makes detection of a human body from some larger distance impossible. Other materials, e.g. metal, have a lower absorption coefficient with maximum value for shorter wave (200-400 nm) than for the biological tissue. It is difficult to detect the properties of metals and tissues by optic techniques because the wave has to penetrate into the human body, to reveal the differences between the optical characteristics (e.g. absorption coefficient). Measurement only the reflection coefficient does not allow for distinguishing different types of materials such as living tissues or metals.

In electromagnetic methods the proximity sensor always emits the electromagnetic field, which is disturbed (absorbed, etc.) by the object placed near the sensor. The disturbances of the electromagnetic field can be then recorded and utilized for detecting and recognizing of the object. Depending on the electromagnetic properties of the different types of proximity sensors, specific sensors are always oriented on detecting slightly different objects. For example impedance measurements can be used to detect of the person in the bathtub [3].

In general, a coil-object interaction is based on the fact, that the alternating magnetic field of the coil is inducing eddy currents in (conducting) the object. Induced eddy currents create a magnetic field that opposes the magnetic field that created it. The magnetic fields of eddy currents, deriving from the object, induced the electromagnetic field in the coil which resulting a change in its impedance [4]. Additionally, the inductance of the coil depends on the frequency, and this dependence will also have an impact on the impedance of the coil. Those principles are utilized in inductive sensing method, whereas capacitive sensing mechanism is based on the measurement of displacement currents [5].

There are two known types of coil interaction with the nearby object, namely, capacitive (electric) mechanism and inductive (magnetic) mechanism. The electrical properties of the object determine which of these mechanisms will be dominating. Capacitive proximity sensors are usually used for detection of the non-magnetic objects, which conductivity is low, thus the human – system interaction requires contact with the sensor’s surface. Wimmer in [6] presents a game in which user controls a ball by walking on the top of a metal sensor antenna. The measuring parameter is a change of a capacitance. Touchless 3D gesture recognition described in [7] allows in near-field of a sensor ambient detection a single human finger or a whole hand. However, this approach has not been checked in the case of detecting a fingers living tissue. Likewise in [8], when a RF – capacitive proximity sensor was used to detect the presence of human hand equipped in special gloves nearby a chainsaw, and the system turn off the power.

Inductive proximity sensors are usually applied for the recognition of magnetic objects of high conductivity. An example of such device is inductive proximity sensor designed to locate metal shrapnel during surgery, reported in [9]. A combination of inductive and capacitive properties was utilized in conductive-capacitive proximity sensor for seat occupancy sensing [10].

Living tissue has a low conductivity. The technique in which the inductive method is used for measurements of electromagnetic properties of biological tissue is called magnetic induction spectroscopy. In [11] the requirements and limitations of developing a system for biological tissue characterization were described. The estimation of the dielectric parameters (conductivity, dielectric constant) of biological tissue is realised by measurements of the magnetic field at the wide range of frequencies. However, there are some limitations of such system, e.g. the requirement of the...
placement of an object between transmitting and receiving coils, which demands the adequate place and specific measurements procedure. Thus, it cannot be utilized for measurements of living objects anywhere.

Almost all presented methods require the separation of the living tissue and metal object from their natural environment. In real ambient exist not only those two kind of materials as metal or living tissue but also plastics, cements, plants, organic etc. in various configurations (e.g. a person with a dog, a motorcyclist on a motorcycle, a tree, a street light). They all cause that description of an object utilizing only electrical properties in one frequency is not enough. A sensor for detection of the living tissue and metal materials from real environment should also be able to recognize the geometry such as shape, distance from sensor and obviously kind of material.

In this paper we present the preliminary concept of utilization of the simple inductance proximity sensor for living tissue detection. The differentiation between living tissue and the metallic (conductive) objects is analyzed. As a differentiating parameter, the ratio of real to imaginary part of the reflected impedance is considered. Impedance model is analyzed in a wide range of frequency in order to enable recognition from complex surrounding living objects, their location, size and shape.

2. Material and methods

2.1. Impedance model

In terms of electrical properties the living tissue is a dielectric, which in contrast to metals, has a low conductivity. Properties of a material can be described by two passive electromagnetic properties, namely conductivity and permittivity.

The parameter which determines the dielectric properties of materials is the complex permittivity (inclusive the relative permittivity and conductivity), \( \varepsilon^* \) expressed as [12]:

\[
\varepsilon^* = \varepsilon' - j \varepsilon'' - j \frac{\sigma_s}{\omega \varepsilon_0},
\]

where \( \varepsilon' \) and \( \varepsilon'' \) are respectively real and imaginary part of relative electric permittivity, \( \sigma_s \) is the static conductivity conductors, \( \varepsilon_0 \) - the permittivity of free space and \( \omega \) – the angular frequency.

Another description of dielectric properties is presentation them as the complex conductivity:

\[
\sigma^* = \sigma(\omega) + j \omega \varepsilon(\omega),
\]

In biological tissue when frequency is increasing the conductivity has the same trend, and the permittivity has opposite behavior [12]. These changes are not the same in a wide range of frequency. The different situation is observed in metal materials [4], where there are large values of conductivity (e.g. copper has \( \sigma = 58.6 \times 10^6 \text{ Sm}^{-1} \)) and the relative permittivity is equal to 1. Further, these parameters for metal materials are independent of frequency. Therefore using several different frequencies for electromagnetic measurements living tissue and metal materials may make possible to distinguish them.

For living tissue, one of three ranges called \( \alpha \)-, \( \beta \)- or \( \gamma \)-dispersion is observed in the multifrequency measurements. A dielectric dispersion, which is termed \( \beta \)-dispersion, is shown at a certain frequency of electric field (i.e. characteristic frequency) [13]. About 90% of the composition of human body is water. At the frequency range 10 kHz – 10 MHz (\( \beta \)-dispersion) this hydration state is well reflected by the frequency-dependence of the conductivity [11]. With increasing frequency the additional contribution of the intracellular fluid volume causes a significant increase of the conductivity compare to the lower frequencies.

When an object appears in the vicinity of a sensing coil a circuit can be treated as a contactless transformer. The presence of the object changes values of parameters, which is reflected in the impedance of a sensing coil [14].

The issue of measuring a change of coil impedance for the detection of materials of different conductivities is schematically presented in Figure 1.
Mortarelli [15] based on Geselowitz considerations [16] proposed the equation describing mutual impedance changes of $\Delta Z$. This relationship has applied Lorentz reciprocity relation. The formula is presented below:

$$\Delta Z = -\frac{1}{I^2} \int \Delta \sigma^* E_a E_b \, dv,$$

(3)

where the complex conductivity change $\Delta \sigma^*$ is determined by:

$$\Delta \sigma^* = \Delta \sigma + j \omega \Delta \varepsilon$$

$\Delta \sigma$ (\(\Delta \varepsilon\)) represents conductivity (permittivity) changes in the considered volume, which causes change in the field distribution from $E_a$ to $E_b$. The volume of integration $V$ includes the region where properties of the medium are changing. For biological tissues and metals there is no change in permeability so magnetic field component $H$ has no influence on impedance change [17, 18]. In some situations it is useful to simplify calculations and assume that $E_a \approx E_b$ i.e. the field distribution is assumed not to be disturbed by conductivity change (or this disturbance is small). We have compared this approach with assumption that the fields are not the same and difference is caused by different properties of material for half space $z>0$ (region of coil) and $z<0$ (region of disturbance). This is also simplification, but allows using explicit formula for vector potential, and relation with the electromagnetic fields $E_a$ and $E_b$:

$$E = -j \omega A_\phi,$$

(4)

thus:

$$\Delta Z = \frac{\omega^2}{I^2} \int \Delta \sigma^* A_{\phi,a} A_{\phi,b} \, dv,$$

(5)

$\Delta \sigma$ is independent of the region of integration so is treated as a constant. The definition of $A_\phi$ is taken from [19, 20]:
\[ A_{\phi,a}(\rho,z) = \frac{\mu_0 I a}{2} \int_0^\infty J_1(\xi \rho) J_1(\xi a) e^{-\lambda_0 z - h} \frac{\xi d\xi}{\lambda_0}, \quad (6) \]

where

\[ \lambda_0 = \sqrt{\frac{\xi^2 - k_0^2}{\lambda_0}}, \quad k_0^2 = \omega^2 \mu_0 \varepsilon_0, \]

and \( \mu_0 \) is permeability of free space and \( a \) is radius of the coil.

While for a heterogeneous medium:

\[ A_{\phi,b}(\rho,z) = \frac{\mu_0 I a}{2} \int_0^\infty J_1(\xi \rho) J_1(\xi a) e^{\lambda_1 z - h} \frac{2\xi d\xi}{\lambda_0 + \lambda_1}, \quad (7) \]

where

\[ \lambda_1 = \sqrt{\frac{\xi^2 - k_1^2}{\lambda_1}}, \quad k_1^2 = \omega^2 \mu_0 \varepsilon_1 - j \omega \mu_0 \sigma_1, \]

Eqs.6-7 are true for \( z<0 \), i.e. in the region where the conductivity changes are expected. The region of \( z>0 \) is neglected in this approach. A graphic representation of the considered model is shown in Figure 2 where \( a \) is radius of the coil, \( h \) is a coil – cylinder distance, \( R \) and \( H \) are radius and height of the cylinder, respectively. The cylinder is coaxially located under the sensing coil. By modifying the complex conductivity \( \sigma^* \), the cylinder radius \( R \) and height \( H \), a frequency operation \( f \), and the distance \( h \) (the dimensions of the coil have been constant), it is possible to calculate impedance changes of the coil for both types of media (dielectric or conductive) appearing in the proximity of the inductive sensor.

Estimation of the impedance change of the coil induced by the presence of the human tissue or a conductive material in the sensor proximity was realized by numerical simulations according to the formulas presented above. Subsequent values of the complex conductivity and the relative proximity for each frequency were taken from Gabriel tables for ovine muscle tissue [12].

Apart from the impedance modeling, measurements of the living tissue were carried out as well. The measuring set up was composed of a single coil, a metal cylinder, the impedance analyzer and its dedicated software to control measurement parameters. Measurements of living tissue were executed on the volunteer arm. The circular sensor coil was constructed by winding 10 turns (0.15 mm in diameter) of the total inductance 12 \( \mu \)H and the 4 cm radius of the coil. Measurement protocol included measurement the impedance of: empty coil, coil in the proximity of metal cylinder or human arm localized above the sensor. Measurements were performed using Solartron SI 1260 Impedance/Gain-Phase Analyzer in the frequency range from 10 kHz up to 1 MHz using 11 points per decade spaced uniformly in logarithmic scale (1 second for each frequency for metal cylinder, while for volunteer arm it was increase to 5 seconds).

The measurement results were verified using the simple transformer model [21]. However the secondary winding of the transformer is heavy to calculate since its values depend on the object location and parameters. Thus we use simplification that load impedance is equal to metal and arm properties, while secondary inductance is equal to primary one. The coupling factor \( k \) was estimated to obtain results similar to measurement one and was set to 0.55. To obtain more realistic results, transformer model include capacitance coupling also. The value of this capacitor was set to 1nF.

3. Results

The results were analyzed for single turn of the radius coil \( a = 0.5 \) m and four changing parameters: a frequency \( f \) (from 100 kHz to 10 MHz), the coil – cylinder distance \( h \), a cylinder height \( H \), and the radius of the cylinder \( R \) (\( h, H \) and \( R \) from 0.05 m to 2.5 m). In a single simulation only one parameter was changing. The base parameters (were one of the other was changing) were equal to \( f = 1 \) MHz, \( h = \)
$2a, H = 2a, R = a$. The impact of the change of those parameters on the value of the impedance (real, imaginary part, ratio imaginary to real) was investigated.

The relationship of the real and imaginary parts of the impedance for metal and tissue for different distances between coil and the cylinder are illustrated in Figs. 2a and 2b. The influence of the cylinder height is shown in Figures 3a-3b. Figure 3a presents the relation of the real parts of the impedance for metal and tissue for different cylinder height. The imaginary part of the impedance as a function of the cylinder height is shown in Figure 3b.

**Figure 2.** The real vs. real (a) and the imaginary vs. imaginary (b) part of the impedance. Both for various coil – cylinder distance $h$ (simulation).

**Figure 3.** The real vs. real part of the impedance (a), and the real part of the impedance (b). Both for various cylinder heights $H$ (simulation).
Figure 4. The real vs. real part of the impedance (a), and the imaginary vs. imaginary part of the impedance (b). Both for various cylinder radii $R$ (simulation).

Figure 5. The real part of the impedance (a), and the ratio of the imaginary to the real part of the impedance for metal and tissue (b). Both for various cylinder radii $R$ (simulation).

Figure 6. The Cole-Cole plot for tissue (simulation) (a), and human tissue (measurement) (b). The influence of the cylinder radius on the measured impedance was tested, as shown in Figures 4a-4b. The relation of the real part of the impedance as a function of the cylinder radius is shown in
Figure 5a. Figure 5b presents comparison of the imaginary and real part of the impedance for considered materials. The relationship between the real and the imaginary part of the impedance for tissue as a function of frequency obtained from simulations is shown in Figure 6a. The error bars (Figure 7b) show the standard deviation.

Figure 7. The ratio of the imaginary to the real part of the impedance from simulations (a), and from measurements with the standard deviation (b).

Figure 8. The ratio of the imaginary to the real part of the impedance for transformer model.

Similar plot for the human tissue obtained from measurement as seen in Figure 6b. The ratio of the imaginary and to the real parts of the impedance for metal and tissue obtained from simulations and measurements respectively as illustrated in Figures 7a and 7b. Figure 8 shows the same ratio as in Figure 7 for transformer model.

4. Discussion
Burrows [22] was the first, up to our knowledge, who introduced the use of reciprocity in eddy current probe analysis. Similar approach for biomedical applications was derived by Geselowitz [16]. Further on it was generalized for nonquasi-static sinusoidal sources and fluctuating geometry by Mortarelli in 1980 [15]. Because of the complexity of the problem one can consider the simplified assumptions: the change in the electrical field caused by introducing disturbance is so small that the field is the same as in the case without disturbance. This assumption is valid in the case of relatively small disturbance and/or small dielectric properties change introduced by the disturbance. This allows approximating the field $E_b$ in (4) by $E_a$, thus simplified numerical calculations. Otherwise the numerical methods such as FEM had to be used to calculate the $E_b$. We have made similar approach in biomedical applications [13, 23], where these assumptions were valid and gave good results. However, the difference in
dielectric parameters between air and disturbance are so large that this simplification may not be valid. Because of this we have used another simplification, i.e. the disturbance expands in the half space $z<0$. The simulations show that the impedance change rapidly decreasing as a function of coil – cylinder distance and those are similar for the tissue and metal (Figure 2). The vector potential decay for metal is so fast that the height of the cylinder has no influence on impedance change. This is opposite to the tissue (Figure 3). However, even in that case, larger values of the height of the cylinder do not have much influence on the impedance. In the considered range of the cylinder radius, its influence on the impedance is similar in the case of metal and tissue (Figures. 4-5). The main difference is in the amplitude of the signal – it is larger for the real part in the case of tissue, while smaller for the imaginary part of the impedance.

The simulations of the impedance change show that our results are not inconsistent with those obtained by Cheng [19] for half space (our results are smaller due to smaller disturbance size). The main difference in the impedance change for metal and living tissues is that for the metal the permittivity can be neglected comparing to conductivity. It means that sensitivity is multiplied by real number, which is only the enlargement of the value. In the case of living tissues the real and imaginary part of the complex conductivity are similar, i.e. sensitivity (complex number) is multiplied by another complex number so resulting real and imaginary part of the impedance is dependent of both parameters in more complex way.

The simulation results were confirmed by measurements (Figures 6). It follows from the simulation and measurements that metal and living tissue can be differentiate basing on the ratio of imaginary to real part of impedance change measurements (Figures 7-8 and Figure 5b). However the time of measurements was too long for practical applications but it was increased to obtain more reliable results.

From the presented study it is obvious that multifrequency measurement allows distinguishing between tissues and metal. Similarly the dependence of the real and imaginary parts of the impedance on the distance from the coil is different for tissues and metal. The size of the detected object influences the amplitude of the signal. In the case of the tissues the relative permittivity is quite large, so its influence on the reflected impedance is large and allows distinguishing tissues from the metal.

5. Conclusions
The presented simulations and measurements allow to conclude that it is possible to detect and differentiate tissues from metal objects using multifrequency measurements basing on the ratio of imaginary to real part of impedance change. The amplitude of measurement signal depends on the size, the location and the complex conductivity of the detected object. Thus it may be possible to detect object and determine its approximate location and size. However, due to complex signal dependence of these parameters more studies are required.

6. References
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