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ANTENNA ANALYSIS AND OPTIMISATION
FOR DEEPLY IMPLANTABLE MEDICAL SENSOR TRANSPONDERS

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ABSTRACT

Deeply implanted sensor transponders are of interest in treatment of cardiovascular diseases. In such systems only small antennas in shape of a stick are supposed. To make a sensor transponder operable, an optimisation of such an antenna is necessary. Therefor a mathematical expression is derived, that makes optimisation possible. A mathematical model is derived, to describe physical effects. Moreover, the influence of encapsulation and human tissue in direct contact to the antenna is analysed. Finally, an optimisation is done for typical requirements of such a system. Measurements validate the theoretical examinations.

Index Terms— Sensor Transponder Medicine Implant Antenna Energytransmission Human Tissue Optimisation

1. INTRODUCTION

The use of sensor transponder technologies in medicine opens valuable possibilities in the therapy of human cardiovascular system diseases. Medical studies [1] have shown, that the treatment of cardiovascular disease can be significantly improved by continuous monitoring of parameters such as blood pressure, temperature, and so on. A deeply implanted sensor transponder in human body can measure cardiovascular parameters and send it to a reader outside of the body. Implants normally stay inside the body for a longer period. Thus, a supply by a local battery is not possible, only so-called passive transponder systems are of interest. There are several requirements that have to be kept in mind. For example, a large transmission distance (up to half a meter for corpulent patients), low antenna dimensions (catheter implantation) and the influence of human tissue. Today, no system exist, that meet all these requirements. This work is focused on the analysis and optimisation of transponder antennas for such a system. Antenna characteristics will be investigated influenced by the encapsulation and human tissue. With the help of antenna models and mathematical expressions, that are derived in this work, an optimisation of antenna parameters is possible.

2. INDUCTIVE ENERGY TRANSMISSION

A sensor transponder system consists of a reader located outside the body and the implanted sensor transponder. The reader has a transmitter to produce an alternating magnetic field and a receiver for the transponder data. The sensor transponder consist of an antenna coil, a chip including analogue frontend, logic and integrated pressure and temperature sensor. Previous studies [2] have shown, than a frequency of 6.78MHz is a good choice to transmit power to the transponder. At this frequency the maximum power transmission is possible. The transmission takes place in the so called nearfield. Only the magnetic component is used. Because of that, coils are used as antennas.

Figure 1 illustrates a sensor transponder system. The transmission channel consists of an antenna coil in the reader that produces an alternating magnetic field, the human body and the antenna coil of the transponder. The current in the antenna coil of the reader is proportional to the time derivation of the flux \( \frac{\partial \Phi}{\partial t} \). Figure 2 shows an equivalent circuit of the inductive transmission channel. The resistors \( R_R \) and \( R_T \) model losses in antennas and human tissue. The current consumption of the transponder load is modelled by \( R_L \). The function of the antenna coil in the reader is...
to generate a magnetic field at the transponders place, that provides it with enough energy for working. The purpose of the transponder antenna is, to produce the maximum possible voltage with the available magnetic field to provide power to the transponder’s electronics. So, the transmission range can be maximised. The channel is modelled by a transformer equivalent circuit. Moreover it includes tuning capacitors at the primary and secondary side. The following mathematical expression is derived from this equivalent circuit that enables an optimisation of the antenna coil. This formula describes the achievable voltage over the load for an available field strength. It includes all parameters that describe the antenna characteristic.

\[
\frac{\left|U_T\right|}{\left|B_T\right|} = \frac{\omega \cdot N_T A_T}{\sqrt{(\frac{R_T}{\omega L_T} + \frac{\omega L_L}{R_L})^2 + (\frac{R_T}{R_L})^2}} \quad (1)
\]

The better the antenna is optimised, the larger is the value of this expression. The expression depends on some geometrical parameters, like the diameter and number of windings and electrical parameters, inductance, loss resistance and load resistance. To enable an optimisation of the antenna, it is necessary to have a mathematical model, that describes the dependences between the parameters. Moreover the influence of the human tissue has to be analysed. This is done in the following section.

3. THEORETICAL ANALYSIS OF IMPLANTED ANTENNA COILS

Following, the electrical characteristics of implanted antenna coils are analysed. Particularly, the influence of encapsulation and of human tissue in direct contact to the windings of the transponder coil are considered. For energy transmission, the parameters inductance, stray capacity and loss resistance are of interest. A part of available power is converted to heat. Stray capacity exists, because of the electric field between the windings. The electric field lines penetrate the encapsulation and the human tissue. These materials have higher permittivities. This causes a rise of the stray capacitance and can make the antenna unusable. In the end, these effects reduce the transmission range, which is not acceptable in this application.

3.1. INDUCTANCE

The human tissue has no direct influence to the inductance, because it has no magnetic behaviour. However the measurable inductance of an antenna coil is influenced by the stray capacity. The following formula shows the interrelation between measurable inductance \(L_S\), the parasitic capacity \(C\) and the real inductance \(L_L\).

\[
L_S = \frac{L_L}{1 - \frac{\omega^2 L_L C}{}} \quad (2)
\]

If the parasitic capacitance is known, the measuremable inductance can be predicted. By inserting the so called self resonant frequency \(\omega_r = \frac{1}{\sqrt{L LC}}\) we get:

\[
L_S = \frac{L_L}{1 - (\frac{\omega_r}{\omega})^2} \quad (3)
\]

If the self resonant drops to the operation frequency \(\omega\), the effect of inductance and capacitance will cancel each other. If the operating frequency is higher than the self resonance \(\omega_r\), the coil will act as an capacitor.

3.2. STRAY CAPACITY

The windings of the transponder antenna are placed on a ferrite rod. They are surrounded by the encapsulation material and human tissue. Figure 3 shows a schematically structure of an implanted transponder antenna coil. Because of the voltage drop across each winding, an electric field appears. The electric field lines are indicated in the figure. There exist electric field lines between each winding, between the different windings, and to the core. Some of the field lines penetrate the encapsulation and the human tissue. Other field lines are just inside the encapsulation.

Figure 4 shows the simplified HF equivalent circuit of an antenna coil. It consists of inductivities \(L_n\) for each winding, resistors \(R_n\) for modelling losses, and capacities. The overall stray capacity is composed of several stray capacities between each winding \(C_t\) and between the core \(C_s\). The field lines belonging to \(C_t\) penetrate just the encapsulation, whereas the field lines of \(C_t\) penetrates the human tissue. With the help of
a mathematical description of this model, the influence of encapsulation and the human tissue can be estimated. Various materials of encapsulation and human tissue can be considered. The influence of geometrical design parameters, like number of windings can be considered, as well. With the following formulas derived from this model [3], the stray capacity can be obtained.

\[
C_t = \frac{\pi^2 D \varepsilon}{\ln \left( \frac{p}{2r} + \sqrt{\left( \frac{p}{2r} \right)^2 - 1} \right)} \tag{4}
\]

\[
C_s = \frac{2\pi^2 D \varepsilon}{\ln \left( \frac{h}{r} + \sqrt{\left( \frac{h}{r} \right)^2 - 1} \right)} \tag{5}
\]

The overall capacity is composed of all single stray capacities together and can be found out by the following inductive formula:

\[
C(n) = \frac{C(n - 2)C_t/2}{C(n - 2) + C_t/2} + C_s/2 \tag{6}
\]

Now, the influence of encapsulation and human tissue can be discussed. Geometrical parameters, like the dimension of the core, are given by the implantation technique. A searched parameter is the optimal number of windings. Additionally, one of the most important questions is, if the number of windings is limited by the parasitic capacity.

First of all, the influence of the human tissue is discussed. With the help of the formulas, the over all stray capacitance is calculated for several number of windings. Figure 5 shows the result. The over all stray capacitance of the transponder antenna is shown for different kinds of surrounding materials. In all cases, silicone was chosen as encapsulation material. For each material, the corresponding permittivity at the operating frequency was used [4]. First of all, it can be said, that the stray capacitance is affected by the surrounding material. In an antenna coil with two windings, blood causes a value of 18pF, that is 25 times higher than 0.7pF for air. Heart tissue has approximately the same effect. The over all capacitance is decreasing with rising number of windings. The reason is, that the over all capacitance of series connected capacities is smaller than the value of one single capacity. Moreover it can by seen, that the capacitance will not change significantly anymore, for more than about 20 windings. In this case, the capacities between the windings and the core \( C_s \) are decisively. To verify this, the over all capacitance is calculated for different kind of encapsulation materials. Figure 6 shows the result.

Fig. 4. Equivalent circuit of implanted antenna coil

Fig. 5. Stray capacitance over the number of windings for several kind of human tissues

Fig. 6. Dependency of over all capacitance on the number of windings for different encapsulation materials
Fig. 7. Maximum Recommend frequency over number of windings

The reason for this is, that the inductivity rises faster than the parasitic capacitance falls with the number of windings. In this application, an operating frequency of 6.78MHz or 13.56MHz is of interest. These frequencies are shown by the dashed lines. It can be said, that antenna coils with no more than 20 windings can be used for 13.56MHz and not more than 43 windings for 6.78MHz.

3.3. LOSSES

Losses in antenna coils exist in the ferrite core, the wire, and the human tissue around the coil. A part of the energy is converted to heat. Losses in the wire are caused by the ohmic resistance, skin and proximity effects. Ferrite losses are caused by magnetisation of the material and eddy currents in the core. These effects are frequency depended.

**DC resistance**
The DC or ohmic resistance is caused by the limited conductivity of the wire, that means without frequency depending effects. It depends on the length of the wire, the thickness and the conductivity of the used material. The ohmic resistance should be expressed as a function of the number of windings respectively the inductance. With the following mathematical expression the DC resistance can be calculated:

\[
R_{DC} = \frac{N_R D}{\sigma \pi d^2 / 4}
\]

with \(d\) diameter of the wire and \(\sigma\) the conductivity of the material. E.g. for copper \(\sigma_{Cu} = 57 \, \text{Sm/m}^2\). For a cylindric antenna coil \(D = 1.5 \, \text{mm}, \, d = 0.15 \, \text{mm}\) and \(N = 10\) the DC resistance becomes \(46.6 \cdot 10^{-6} \, \Omega\).

**Skin Effect**
Every electrical current is surrounded by a magnetic field. In case of ac current, eddy current will be induced in every conductive material next to the field. Insight the conductor, such eddy currents are as well. These eddy currents itself cause magnetic fields. These fields in turn interact with the current. In consequence, the current flow is driven to the surface of the wire. The bulk is currentless, and the cross section of the wire is not completely used. The resistance of the wire seems to rise. This effect is called skin effect. The ac resistance caused by this effect could be calculated with the following expression [6]:

\[
A_{skin} = R_{DC} \cdot \left( x + \frac{1}{4} + \frac{3}{64x} \right), \quad m \ln x = \frac{d}{4} \sqrt{\pi f \sigma \mu}
\]

Thus, the losses caused by the skin effect can be calculated.

For example, the dc resistance caused by skin effect for a cylindric antenna coil with \(D = 1.5 \, \text{mm}, \, d = 0.15 \, \text{mm}\) and \(N = 10\) at 6.78 MHz amounts to \(9 \, \text{m} \Omega\).

**Proximity Effect**
If a wire is arranged to a coil, an additionally rise of the resistance will be observed. The reason is, that the magnetic field of induced eddy currents interacts with adjacent windings. This effect can be described mathematically. Kelvin-Besselfunctions are necessary. An expression to determine the ac resistance is given in [7]:

\[
R_{AC} = R_{DC} + \frac{\gamma \left[ \text{ber}_{2} \gamma \text{bei}_{2} \gamma - \text{beir}_{2} \gamma \text{ber}_{2} \gamma \right]}{\text{ber}_{2} \gamma + \text{beir}_{2} \gamma - 2\pi \gamma \text{ber}_{2} \gamma + 2\pi \gamma \text{beir}_{2} \gamma}
\]

with \(\gamma = \frac{d}{\delta \sqrt{2}}\) and \(\delta\) the so called skin depth. “bei”, “ber” are the Kelvin-Besselfunctions. The geometry of the conductor is considered.

Therefore, the losses caused by proximity effect can be described analytically.

**Losses in human tissue**
The losses inside human tissue for different frequencies were analysed in [2]. It can be said, that about 2% up to 7% of the energy is lost at 6.78 MHz. At 13.56 MHz about 5% to 24% is lost.

**Losses in Ferrite Material**
Additionally losses occur in the ferrite core. These are losses caused by eddy currents so called hysteresis losses. These effects are analytically difficult to be described. Because of that, it is more practicable to use an approximation with real measurement results. A polynomial function is fitted to these measurement values. The measurements were done with a 2.5 mm x 10 mm ferrite rod that matches the requirements of the application.

**Modelling of antenna coil**
Now all loss effects are listed and the behaviour of the used antenna coil can be investigated. It is possible to build a model that describes the dependences between the physical parameters inductance, frequency and loss
resistance. All mathematical expressions and the fitting function were included into a Matlab [8] function. Figure 8 shows the result. The z-axis represents the loss resistor. The x-axis is the inductance and y-axis the frequency. For all frequencies and inductivities, the loss resistance is known yet. With this model and the formula 1, it is possible to do an optimisation. This is done in the following section.

4. OPTIMISATION, CONSTRUCTION AND PRACTICAL VERIFICATION

With the help of the formula derived from the equivalent circuit in section 2 and the models derived in section 3, an optimisation of an implantable antenna coil is possible. With measurements on realized antenna coils inserted into a phantom fluid, the theoretical results are verified.

Geometrical parameters like core length and diameter are limited by the implantation technique. Hence, the number of windings respectively the inductance is optimised. By taking a look at formula 1, it can be seen, that the voltage at the load has a non linear dependence of the inductance. The inductance respectively the number of windings, is searched, for which the voltage is maximal. All voltage values were calculated with an field strength typical for the application. Figure 9 show the results. The reachable voltages at a load of \(50k\Omega\) at 6.78MHz are displayed, for inductances from \(100nH\) to \(20\mu H\). The crossed curve shows the measurement results. The optimal inductance is \(4\mu H\). This value is reached with 20 windings. Figure 10 shows a realized antenna. It was build with a 0.15 mm copper wire on a 1.5mm x 8mm ferrite rod.

Now feasibility of an antenna coil with these parameters should be validated by taking care of stray capacity. By taking a look at figure 7 it can be stated, that this antenna coil is usable for frequencies up to 15MHz.

<table>
<thead>
<tr>
<th>Material</th>
<th>Air</th>
<th>Encaps</th>
<th>Phantom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permittivity</td>
<td>1</td>
<td>2.69</td>
<td>12.54</td>
</tr>
<tr>
<td>Measured Ind.</td>
<td>(5,7\mu H)</td>
<td>(5,9\mu H)</td>
<td>(6.3\mu H)</td>
</tr>
<tr>
<td>Self Resonantf.</td>
<td>(58,MHz)</td>
<td>(46,MHz)</td>
<td>(13,MHz)</td>
</tr>
</tbody>
</table>

Table 1. Determination of self resonant frequency by measurements

The resonant frequency and the effective inductance were measured with a network analyser and an LCR-meter. For this, an antenna coil was build with 20 windings on a 1.5mm x 10mm ferrite core. To simulate the influence of the human tissue, the antenna coil was placed inside a phantom fluid. This fluid was prepared following a recipe described in [9]. The dc inductance of the builded antenna coil is about \(4\mu H\). The measurements where done at 6.78MHz.
1.6. The permittivity of silicone is specified with 2.69. Inside the phantom fluid, the self resonant drops additionally around a factor of 12.52. The permittivity of the fluid is about 12.54.

5. CONCLUSION

With the help of a mathematical expression, derived from an equivalent circuit of the transmission channel, an optimisation of an antenna coil was performed. Loss effects were considered by a developed model. The influence of the encapsulation and the human tissue to the stray capacity was analysed. For the presented application, a ferrite coil with 20 windings is an optimal choice. Usability was validated by determining the self resonant frequency. Practical measurements verified the influence of encapsulation and human tissue.

6. REFERENCES


[9] Standard test method for measurement of radio frequency induced heating near passive implants during magnetic resonance imaging.