Modelling and Simulation of Implantable Medical Electronics Communication Devices

Hao YANG1, Shuang ZHANG1,2, Jing XIAO3, Yihe LIU*2

1The Engineering & Technical College, Chengdu University of Technology, Leshan614000, China
2College of Computer Science, Neijiang Normal University, Neijiang641000, China
3Air force Logistic College, Xuzhou 221000, China

Abstract — ‘Implantable medical electronics’ is an important part of modern medicine. It is widely applied to meet the needs for long monitoring time, steady transmission signal, small noise and easy controllability, by communicating with external terminals. The need for steady signal, small noise and to cause minimum damage to the host living tissues, the galvanic coupling intra-body communication has become the new wireless mode for implantable devices. In this paper we study the channel characteristics for these devices in 3 steps: i) the active field single-layer intra-body communication channel model is formulated based on Maxwell equations, and the analytical solution is derived for the potential distribution from: ii) the cylinder center to the source point and iii) from the source point to the surface. Then, using Matlab2010b simulation the potential distributions were obtained for: i) the cylindrical surface where the source point is placed, and ii) the cylinder surface. To verify correctness, a numerical solution model was formulated using the finite element method. By analyzing the two models’ results, we conclude that the analytical solution model is correct. To describe channel characteristics, the signal attenuation rate was analyzed, and we found the signal attenuation was two to twenty-six dB within the detection range of the meter. Thus the communication method is superior to others and provides theoretical basis for further experiments.

Keywords—Implantable medical electronics; galvanic coupling; intra-body communication; channel modeling; analytical solution model

I. INTRODUCTION

The implantable medical electronics is an electronic device embedded in living bodies or human tissues. It has two functions, one is to monitor or record long-term change of normal or abnormal living entities’ physiological and biochemical parameters, and thus diagnose and treat some diseases, so as to achieve direct internal measurement and control when they are in unrestricted and natural condition [1]. The other auxiliary equipment used to send signal to living bodies or human bodies, so as to control or improve abnormal biological tissue’s functions [2]. The implantable medical electronic measurement and control device has the following advantages: (1) to ensure continuous and real-time measurement and control of all physiological and biochemical parameters under living bodies’ natural physiological status; (2) after the implantable measuring device is used, all information in living bodies need not be measured through skin, so as to reduce many interference factors and obtain more accurate date; (3) facilitate direct regulation and control of organs and tissues, so as to get ideal stimulation and control response and benefit recovery of impaired functions and disease controlling; (4) used to treat some diseases, such as epilepsy[3], quadriplegia[4]; (5) used to replace some organs’ functions[5-8], such as cardiac pacemaker and cochlea. Therefore, the development of the implantable electronic devices will be an important direction of biomedical electronics in the twenty-first century.

In order to realize medical electronic devices’ functions, the communication with the external must be accomplished. There are two common communication modes, the wired communication and the wireless communication. In the wired communication, the communication wire is used to connect the implantable devices with the external devices as to achieve signal transmission, for example, wired cardiac pacemaker and artificial retina. Because the communication wire needs to penetrate biological tissues, this causes infection easily and produces complication. When living bodies or human bodies move, the communication wire also bring noise so as to decrease signal noise ratio. The wireless communication includes electromagnetic coupling communication [10], frequency radio communication [11-12] and intra-body communication [13]. The first two have broad bandwidth and have high communication frequency during communication, thus they have high communication speed. Meanwhile, because the first two communication modes need high communication frequency, in the high-frequency environment, human tissues have a strong shielding effect on the signal, this leads to very large signal attenuation. Since the high-frequency radiation damages living bodies or human tissues greatly and larger implantation space is required to place communication coil or antenna, the two methods are unsuited for implantation at brain, marrow and chest, that is to say, the implantation position is restricted.

In the galvanic coupling intra-body communication, human tissues are used as a signal transmission medium [14], avoiding complicated wiring; meanwhile, because the...
signal couples directly with human body, the space placing communication coil or antenna need not be considered; its communication frequency lies below 1MHz, the radiation is small and the influence on tissues is very small, so the placement position of the implantable devices is not greatly restricted.

In order to study the signal transmission mechanism in the channel and provide theoretical support for communication channel, the theoretical model of the communication channel should be built. There are three theoretical models of the communication channel, namely simplified circuit model, numerical solution model and analytical solution model. In the first model, human tissues are considered to be electronic components, and the model is built by simplifying the circuit. This model is easy to build and its computation is simple; but this model’s repeatability is poor, when channel parameters (e.g. communication frequency, implantation depth and communication distance) change, electronic components’ properties need re-definition and the model needs re-derivation. Therefore, the effect is unsatisfactory during studying multi-frequency implantable intra-body communication channel characteristics.

The numerical solution model and the analytical solution model make up the disadvantages of the first model, and they have strong repeatability. When channel parameters (e.g. communication frequency, implantation depth and communication distance) change, the relevant result can be obtained only by setting the relevant parameter model. However, computation of the numerical solution model depends on the interpolation function and the unit resolver, and the sensitivity matrix cannot be formed, so the computation cost of this model is extremely large. For this reason, the optimal result cannot be achieved in studying multi-frequency implantable intra-body communication channel characteristics.

### TABLE 1 COMPARISON BETWEEN ANALYTICAL SOLUTION MODEL AND NUMERICAL SOLUTION MODEL

<table>
<thead>
<tr>
<th>Model type</th>
<th>Modeling method</th>
<th>Repeatability</th>
<th>Resolver</th>
<th>Interpolation calculation</th>
<th>Calculating speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical solution</td>
<td>Mathematical modeling</td>
<td>Very good</td>
<td>Yes</td>
<td>No</td>
<td>Very fast</td>
</tr>
<tr>
<td>Numerical solution</td>
<td>Finite element method</td>
<td>Ordinary</td>
<td>No</td>
<td>Yes</td>
<td>Ordinary</td>
</tr>
</tbody>
</table>

The analytical solution model compensates weaknesses of the simplified circuit model and the numerical solution model, it has stronger repeatability and its calculation is independent of the interpolation function and the unit resolver; besides, it can better establish the sensitivity matrix, so the numerical solution model has very small calculation cost. Although the model is only suited for some simple geometry, it is proved through PUN’s experiments[14] that, the analytical solution model obtained when human forearm is simplified as a multi-layer cylinder approximates the result from the experiment on human arm surface very much. Therefore, application of the analytical solution model in intra-body communication research is feasible.

In this study, the single layer cylinder model was built by means of the Maxwell equation in combination with the quasi-static approximation condition, so as to analyze signal distribution in the cylinder. To verify the correctness of the model solution, the finite element method was also used to build the numerical solution model, and the same electrical parameters with the analytical solution model was input to verify the solution.

### II. MODELLING

#### A. Modeling Analytical Solution Model

In the quasi-static electromagnetic field [15], the electric field (vector) \( \mathbf{E} \) may be expressed as the gradient of the electric potential (scalar) \( \Phi \), so Equation (1) can be derived. The current distribution \( \mathbf{J} \) can be obtained through the Ohm’s law, so Equation (2) can be obtained.

\[
\begin{align*}
\mathbf{E} &= -\nabla \Phi(
\rho)
\end{align*}
\]

\[\mathbf{J}_0 = \sigma \mathbf{E} \tag{2}\]

where \( \sigma \) is the conductivity of the medium. The current distribution in the quasi-static electromagnetic field is the superposition of the induced current and the exciting current, so Equation (3) is derived.

\[
\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_{\text{impressed}} \tag{3}
\]

where the exciting current (scalar) may be indicated by

\[
|\mathbf{J}_{\text{impressed}}| = \frac{I}{sW}.
\]

The divergence of Equation (3) can be derived as follows:

\[
\begin{align*}
\nabla \mathbf{J} &= \nabla \mathbf{J}_0 + \nabla \mathbf{J}_{\text{impressed}} \\
&= \nabla \left( \sigma \mathbf{E} \right) + \nabla \mathbf{J}_{\text{impressed}} \\
&= \nabla \left( -\sigma \nabla \Phi(n \rho) \right) + \nabla \mathbf{J}_{\text{impressed}} \tag{4}
\end{align*}
\]

In the statics, \( \mathbf{J}_0 \) indicates the gradient of diffusion ions and \( \mathbf{J}_{\text{impressed}} \) indicates an exciting source field.

In Equation (4), \( \mathbf{J} \) indicates the current of the overall conductor; in the quasi-static electric field, the condition...
\( \nabla \cdot \vec{J} = 0 \) must be satisfied. So the following equations can be derived,

\[
\begin{align*}
\nabla \cdot \left( -\sigma \nabla \Phi (\rho) \right) &= -\nabla \cdot \vec{J}_{\text{impressed}} \\
\nabla \cdot \left( \tilde{\nabla} \Phi (\rho) \right) &= \frac{\nabla \cdot \vec{J}_{\text{impressed}}}{\sigma}
\end{align*}
\]

(5) (6)

where \( \vec{J} \) indicates current distribution (A/m\(^2\)) of the overall conductor.

Let \( J_1 = \nabla \cdot \vec{J}_{\text{impressed}} \), where \( J_1 \) is the source current density of the volume conductor, so Equation (6) can be derived

\[
\nabla \cdot \left( \tilde{\nabla} \Phi (\rho) \right) = \frac{J_1}{\sigma} \delta (\rho - \rho_0)
\]

(7)

where \( J_1 = \frac{I_{\text{sw}}}{\text{wh}} \), \( J_1 \) is the source current density (A/m\(^3\)).

\( I \) is the external injected current.

In the vector field, the Green function may be expressed as follows:

\[
G(\rho, \rho_0) = \delta (\rho - \rho_0)
\]

(8)

On the basis of Equation (7), the electric potential may be expressed as follows:

\[
\Phi (\rho) = -\int_A \vec{J}_{\text{impressed}} \cdot \nabla G(\rho, \rho_0) \, d\rho_0
\]

(9)

In a cylinder with a limited length, the tangential current on the top and the bottom surfaces meeting the boundary conditions are equal to zero; and the current in the tangent direction of the curved surface meeting the boundary conditions is equal to zero. Therefore, the following can be derived:

\[
\left. \frac{\partial V (r, \phi, z)}{\partial \rho} \right|_{\rho = a} = 0
\]

\[
\Phi (r, \phi, z = 0) = \Phi (r, \phi, z = h) = 0
\]

(10)

It can be seen from Equation (9) that the analytical solution of the Green function should be first derived if the analytical solution of the electric potential is desired. Because the multi-layer model is derived from the single-layer model, the analytical solution of the single-layer model is firstly derived.

Suppose the grounding cylinder has a radius of \( a \) and a height of \( h \). If the position of the source point is \((b, 0, c)\), the implantable geometric model can be obtained.

For any source point \((r_0, \theta_0, z_0)\) in the cylinder, its Green function satisfies the following nonhomogeneous linear equation:
I_m (\bullet) and K_m (\bullet) indicate the Bessel functions of the first kind and the second kind, respectively; and I'_m (\bullet) and K'_m (\bullet) indicate their first-order derivatives, respectively, \( \Delta_\theta = \tan^{-1}\left(\frac{s}{2a}\right) \).

(2) When \( r_0 < r < a \), the following may be derived:

\[
G(r, \theta, z_0, \theta_0, z_0) = \frac{1}{h \pi} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left[ A_m \left(\frac{n \pi}{h} r\right) + B_m \left(\frac{n \pi}{h} r\right) \right] e^{\imath \alpha_m (\theta - \theta_0)} \sin \frac{n \pi}{h} z \sin \frac{n \pi}{h} z_0
\]

Where \( A_m = -\frac{I_m\left(\frac{n \pi}{h} r_0\right)}{I'_m\left(\frac{n \pi}{h} a\right)} ; B_m = I_m\left(\frac{n \pi}{h} r_0\right) \)

So the analytic expression of the potential distribution can be derived as follows:

\[
\Phi(r, \theta, z) = -\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{2J_0\left(\frac{n \pi}{h} r\right)}{\imath \alpha m \pi^2} \left[ K_m\left(\frac{n \pi}{h} r\right) I'_m\left(\frac{n \pi}{h} a\right) - I_m\left(\frac{n \pi}{h} r\right) K'_m\left(\frac{n \pi}{h} a\right) \right] \left[ e^{\imath \alpha_m (\theta - \theta_0)} - e^{-\imath \alpha_m (\theta - \theta_0)} \right] \sin \frac{n \pi}{h} z \sin \frac{n \pi}{h} z_0
\]

where \( |J_m| = \frac{I}{\sigma Sw} \), \( s \) and \( w \) indicate the electrode’s width and length respectively; \( \sigma \) is the conductivity of the conductor; \( I \) indicates the density of the injection current; \( I_m (\bullet) \) and \( K_m (\bullet) \) indicate the Bessel functions of the first kind and the second kind, respectively; and \( I'_m (\bullet) \) and \( K'_m (\bullet) \) indicate their first-order derivatives, respectively, \( \Delta_\theta = \tan^{-1}\left(\frac{s}{2a}\right) \).

### B. Modeling Numerical Solution Model

To verify the correctness of the model, COMSOL Multiphysics 4.4 was used to build a numerical solution model with the same geometric model and the same implantation depth with the analytical solution model. The current signal was input through the electrode to analyze signal distribution.

III. RESULT

For further verification, we selected ham sausage material as the filling medium of the cylinder. According to Reference [14], when the communication frequency is 10kHz, the material’s electric conductivity is 1.7s/m. Suppose the cylinder’s length is 2m and its radius is 3.6cm. A pair of electrodes were placed at the point with the...
cylinder radius of 2.6cm, 50cm away from the end point, and the electrode size is 2cm x 2cm. A 20mA current with the frequency of 10kHz is input in the electrode. The cylindrical surface’s potential distribution where the source was placed and surface potential distribution were detected respectively. The calculated results of the analytical solution and the numerical solution is illustrated in Fig. 3, Fig. 4 and Fig. 5.

Fig. 3 Calculated result of analytical solution model at cylindrical surface

Fig. 4 Section potential distribution of numerical solution model at electrode center
By comparing two models’ calculated results, we found that their calculated results are approximate; so we conclude that the solution of the analytical solution model is correct.

However, in relevant research of intra-body communication, particular emphasis was laid on the transmission characteristics of human body channel. In communication theory, the common indexes used to describe channel characteristics include bit error rate, signal to noise ratio, phase shift, attenuation rate and signal distortion, and so on. For the galvanic coupling intra-body communication, signal transmission in human body in the form of conduction current is restricted by human tissues’ electric characteristics to a great extent; therefore, at present, the carrier frequency of transmission signal is generally not high. For this reason, the attenuation rate becomes a main index describing the physical layer properties of human body channel[16]. The signal attenuation rate is defined as follows:

$$A_{\text{Attenuation}} = 20 \log_{10} \left( \frac{V_{RX}}{V_{TX}} \right)$$

$A_{\text{Attenuation}}$ indicates signal attenuation rate; $V_{RX}$ indicates the potential of the detecting point; $V_{TX}$ indicates sending potential.

According to Equation (16), signal attenuation from surface detecting point to the source point can be obtained as shown in Fig. 7.
It can be seen from the figure that, when the detecting point lies on the cylindrical surface where the source point is placed, the signal attenuation is the minimum, about 2dB. In actual detection, it cannot be completely aligned, so signal attenuation of the position slightly distant from the source point needs analysis.

IV. CONCLUSION

The implantable equipment communication is an important method to achieve equipment function and improve equipment performance. To analyze signal transmission mechanism in the channel, we used the analytical solution model to build the galvanic coupling intra-body communication channel model. Potential distribution of the cylindrical surface where the source point was placed and the surface in the channel was obtained through simulation; to verify the correctness of the solution, the finite element method was used to build the numerical solution model. It can be concluded by analyzing two models’ results that the analytical solution model is correct. To describe channel characteristics, we analyzed the signal attenuation rate, signal attenuation was two to twenty-six dB within the detection range of one meter. So the communication method is superior to others and provides theoretical basis for further experiments.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGEMENT

This work presented in this paper is supported by The Key Fund Project of Sichuan Provincial Department of Education under Grant13ZA0003, Grant 14ZB0360, Grant 14ZB0363, Grant 14ZB0352, The Sichuan Province Department of Science and Technology under Grant 2015JY0119, the Key Fund Project of Leshan Science and Technology Bureau under Grant 14GZD046, Grant 15ZDYJ0177. The engineering & technical college of Chengdu University of Technology youth fund under Grant C122014015.

REFERENCES


[12] European Telecommunications Standards Institute, ETSI EN 301 839-1 Electromagnetic compatibility and Radio spectrum Matters (ERM); Radio equipment in the frequency range 402 MHz to 405 MHz for Ultra Low Power Active Medical Implants and Accessories; Part 1: Technical characteristics, including electromagnetic compatibility requirements, and test methods, 2002.


