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Modeling for Intra-Body Communication with Bone Effect

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Abstract—**Intra-body communication (IBC) is a new, different "wireless" communication technique based on the human tissue. This short range "wireless" communication technology provides an alternative solution to wearable sensors, home health system, telemedicine and implanted devices. The development of the IBC enables the possibilities of providing less complexity and convenient communication methodologies for these devices. By regarding human tissue as communication channel, IBC making use of the conductivities properties of human tissue to send electrical signal from transmitter to receiver.**

In this paper, the authors proposed a new mathematical model for galvanic coupling type IBC based on a human limb. Starting from the electromagnetic theory, the authors treat human tissue as volume conductor, which is in analogous with the bioelectric phenomena analysis. In order to explain the mechanism of galvanic coupling type technique of IBC, applying the quasi-static approximation, the governing equation can be reduced to Laplace Equation. Finally, the analytical model is evaluated with on-body measurement for testing its performance. The comparison result shows that the developed mathematical model can provide good approximation for galvanic coupling type IBC on human limb under low operating frequencies.

Keywords- Intra-body communication, galvanic coupling type technique, Maxwell Equations, quasi-static approximation

I. INTRODUCTION

Intra body communication (IBC) is a new, short-range, "wireless" and human base communication technique proposed by T. G. Zimmerman in 1995[1] [2] [3]. By coupling the electric signal into the human body and making use of the conducting properties of human tissue, IBC realizes a short-range "wireless" communication method with less electromagnetic interference and less susceptible to external interference in comparison with existing electromagnetic wave based communication technique[4]. The features of IBC are believed to be able to improve the telemedicine system, wearable system, home health care system and implanted devices[3] [4] [5] [6]. Pilot research in applying the IBC technique in biomedical engineering area [4] further enlightens the research and development of the technological detail of the IBC. It is also expected this "wireless" communication technique can eventually help to reduce the size of the sensors on human body, less power consumption[7], as well as improve stability of overall system.

The Galvanic coupling/Waveguide type technique [3] [4] [6] [7] [8]is an alternative configuration for implementation of IBC. As shown in Figure 1, electrodes of the transmitter are attached to one end of the human body while electrodes of the receiver are attached to another end. When electrical signals are applied to the electrodes of the transmitter, the signal will propagate along the human body in analogue to electromagnetic wave propagate along a waveguide. The electrodes of the receiver, which attached on the other end of the body, detect and convert the information from the transmitter. Unlike the electrostatic coupling technique, the electrical signal propagated via ionic fluid and thus, less dependent on the surrounding environment. Since the technique is relative new, the research of galvanic coupling technology mainly focused on application – especially biomedical application. Although the achieved data rate of Galvanic coupling type technique is low, independent of the earth ground and current propagation within human tissue are more attractive than the electrostatic coupling technique. Based on these reasons, the research direction of the authors is focused on the Galvanic coupling type IBC.

In this paper, the authors proposed a new mathematical model for IBC based on a human limb. Starting from the electromagnetic theory, the authors treat human tissue as volume conductor, which is in analogous with the bioelectric phenomena analysis[9] [10], in order to explain the mechanism of galvanic coupling type technique of IBC. The developed model is still simple and rough; however, with reference to the result of on-body measurement, the model can provide good approximation under low operating frequency.

II. METHODOLOGIES

In this research, solving the galvanic type coupling IBC problem on human limb is focused. The human limb is a convenient site while the proposed approach could be applicable to analyze galvanic type coupling IBC to other location on the human body. Two band-type electrodes are attached close to the wrist and are considered as transmitter of

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the IBC. Another two band-type electrodes are placed close to the elbow are regarded as receiver as depicted in Figure 1.

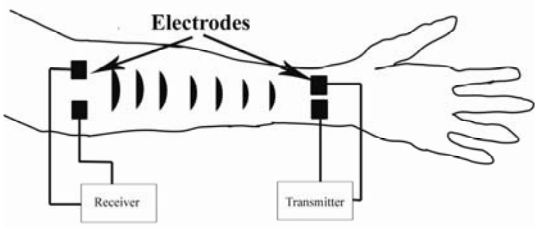

Figure 1 Illustration of galvanic coupling type IBC

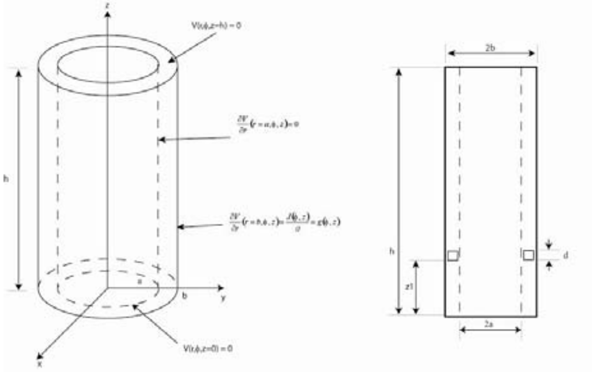

Figure 2 Simplified model for human limb IBC problem with bone

Similar to prior research [11] [12] [13], transforming the IBC problem into mathematical formula is an essential step. It is noticed that human limb is not easy to be expressed mathematically and thus, a regular geometry is selected. Considering the limb is mainly consisted of muscle and bone, the authors attempt to use a hollow muscle cylinder to represent based on the fact that bone can be considered as non-conductor ($\sigma_{\text{muscle}} \approx 0.34$S/m >> $\sigma_{\text{bone}} \approx 0.02$S/m)[14] for general case (as shown in Figure 2). Maxwell Equation is then applied to the problem and solve for the potential induced by the transmitter electrodes. Because the IBC are generally operating in low frequencies[4], the quasi-static approximation can be applied for cases which frequency is less than 100kHz as reported in [9] [10] [13]. The quasi-static approximation states that “if the dimension of the studied problem is less than 1 meter and satisfies Eq.(1), the capacitive effect can be neglected”,

$$\frac{\omega \varepsilon_0 \varepsilon_r}{\sigma} << 1 \tag{1}$$

In Eq. (1), ε_r and σ represent the relative permittivity and conductivity of the tissue and ω denotes the operating angular frequency. In Table 1 the quasi-static approximation with muscle’s electrical characteristics [15] is listed.

	10kHz	100kHz
Conductivity σ	3.4e-1	3.9e-1
Relative Permittivity ε_r	3.0e4	8.0e3
$\frac{\omega \varepsilon_0 \varepsilon_r}{\sigma}$	≈0.049	≈0.114

Table 1 Quasi-static condition for IBC problem

From Table 1, for the operating frequency less than 100kHz, the quasi-static could be applied and according to the prior research, neglecting the propagation effect, capacitive effect and inductive effect, and making use of the homogeneous assumption of the problem; the Maxwell Equations can be simplified to the Laplace Equation. The boundary conditions can be established in according to the IBC model and is defined as:

$$\begin{gathered} V(r,\phi,z=0)=0 \\ V(r,\phi,z=h)=0 \\ \frac{\partial V}{\partial r}(r=a,\phi,z)=0 \\ \frac{\partial V}{\partial r}(r=b,\phi,z)=\frac{J(\phi,z)}{\sigma}=g(\phi,z) \end{gathered} \tag{2}$$

where, V represents the potential throughout the region, σ represents the conductivity of the muscle of human limb and $J(\phi,z)$ depicts the injected current density into the human limb from outside surfaces. The band-type transmitter electrodes are defined as:

$$J(\phi,z)=\begin{cases} 1 & z1 \le z \le z1+d \text{ and } 0 \le \phi \le \frac{\pi}{6} \\ -1 & z1 \le z \le z1+d \text{ and } 0 \le \phi \le \frac{5\pi}{6} \\ 0 & \textit{elsewhere} \end{cases} \tag{3}$$

Since band type electrodes are used, symmetry advantage is vanished. The analytical solution is obtained after solving the given partial differential equation with the given boundary condition,

$$V(r,\phi,z)=\sum_{n=0}^{\infty}\sum_{m=1}^{\infty}\left[I_n(k_m r)+\beta K_n(k_m r)\right]\left[C_{mn}\cos(n\phi)+D_{mn}\sin(n\phi)\right]\sin(k_m z) \tag{4}$$

$$C_{mn}=\begin{cases} \dfrac{1}{\alpha\pi h}\displaystyle\int_{-\pi}^{\pi}\int_{0}^{h} g(\phi,z)\sin(k_m z)\cos(n\phi)\,dz\,d\phi & n=0 \\ \dfrac{2}{\alpha\pi h}\displaystyle\int_{-\pi}^{\pi}\int_{0}^{h} g(\phi,z)\sin(k_m z)\cos(n\phi)\,dz\,d\phi & \text{n}=1,2\ldots\infty \end{cases} \tag{5}$$

$$D_{mn}=\frac{2}{\alpha\pi h}\int_{-\pi}^{\pi}\int_{0}^{h} g(\phi,z)\sin(k_m z)\sin(n\phi)\,dz\,d\phi \quad n=1,2\ldots\infty \tag{6}$$

$$\beta = \frac{\left[I_n(k_m r)\right]'\Big|_{r=a}}{\left[K_n(k_m r)\right]'\Big|_{r=a}} \tag{7}$$

$$\alpha = \left[I_n(k_m r)\right]'\Big|_{r=b} - \beta\left[K_n(k_m r)\right]'\Big|_{r=b} \tag{8}$$

$$k_m = \frac{m\pi}{h} \tag{9}$$

where I_n is the nth order modified Bessel function of the first kind, K_n is the nth order modified Bessel function of the second kind.

III. RESULT AND DISCUSSION

From the aforementioned analytical solution, it is recognized that the solution is more complex than previous publications [11] [12] [13] because both band type electrodes and bone effect are considered into this model. This complexity is believed to bring better modeling of the IBC and, on the other hand, release the constraint of the electrode shape and able to employ irregular shape electrode provided that the shape can be described mathematically. By changing the values of J(ϕ,z) and recalculate C_{mn} and D_{mn}, different electrodes can be included without re-solving the whole equation.

For testing the developed mathematical model, an IBC problem with conditions partly extracted from [3] is employed. Since the developed model is focused on human limb, the A1 and A2 location is chosen. The electrode dimension is not known, thus, we defined the dimension of all electrodes is 2 cm x 1.5 cm. The electrodes of the transmitters are 5 cm separated and located 3 cm from the wrist, while the electrodes of the receiver are also 5 cm separated and situated 5 cm from the elbow. The dimensions of the subject's limb are measured from one of the authors and the length of the limb is 24 cm (h), the outer radius of the limb is 3 cm (a) and the bone is considered as 2 cm (b) in radius.

By evaluating Eq. (4) with the IBC conditions, the voltage induced by the transmitter can be obtained. Figure 3 shows the voltage distribution on the surface of the limb (x=0cm, y=3cm) along z-axis. The potential reaches its highest value near the transmitter electrodes and decreases gradually. Figure 2 shows the voltage distribution on the surface of the limb at 5cm from the elbow, where the electrodes of the receiver located. Figure 4, also suggests the location of the electrode of the receiver in order to obtain higher signal. From the obtain solution, the authors are also able to calculate the "gain" of the IBC; it is around -44dB, which is comparable to the measurement result of Marc Wegmueller, et al.[3] For IBC communication between A1 and A2, below 100kHz, the attenuation is around -55 ~ -50 dB. This suggests that the proposed model is closed to the realistic situation for operating frequency below 100 kHz.

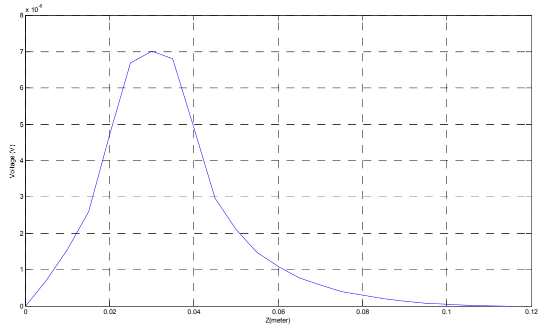

Figure 3 Voltage distribution on the surface of the limb (x=0 cm, y=3cm) along z-axis

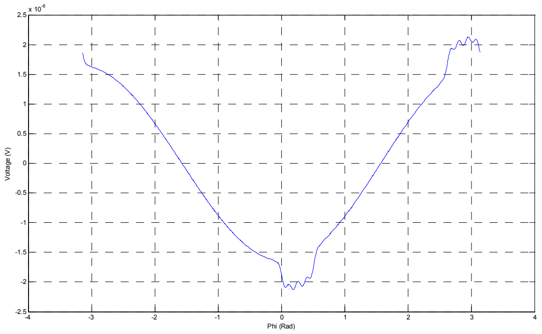

Figure 4 Voltage distribution on the surface of the limb at 5cm (z=19cm) from the elbow

IV. CONCLUSIONS

IBC is a new, different wireless communication technique based on the human tissue. This short range "wireless" communication technology provides an alternative solution to wearable sensors, home health system, telemedicine and implanted devices. The development of the IBC enables the possibilities of providing less complexity and convenient "wireless" communication methodologies for these devices.

In this article, a mathematical model for the IBC problem on a human limb based on quasi-static electromagnetic equations is proposed. This model employs a hollow cylinder to simulate electric signal distribution on a human limb which is mainly constituted by muscle and bone. The resultant analytical solution gives estimation for the attenuation and also provides a selection criterion for receiver electrodes location. Furthermore, by comparing the measurement result of another publication, the analytical model shows that it is capable of providing an approximation for the IBC problem in low frequencies (say <100 kHz).

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