A Gain Measurement in the Liquid Based on Friis Transmission Formula in the Near-Field Region

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Abstract

In 300MHz-3GHz, a probe used in measuring SAR (Specific Absorption Rate) of the mobile communication device is usually calibrated by use of a rectangular waveguide filled with the tissue equivalent liquid. Above 3GHz, however, this conventional calibration has the possibility of inaccurate assessment because the diameter of the probe is comparable with the cross-sectional dimension of the waveguide. Therefore, an alternative calibration for the SAR probe based on another principle is required and is developed by the authors. In our proposed calibration, first, the gain of the reference antenna in the liquid is evaluated by use of two antenna method based on the Friis transmission formula in the conducting medium, and then the electric field radiated by the reference antenna is related to the output voltage of the SAR probe at a point in the liquid. However, the fields are significantly reduced in the liquid and the gain is impossible to be calibrated in the far-field region. To overcome this difficulty, the Friis transmission formula in the conducting medium is extended in the near-field region. In the paper, some numerical and experimental results of estimated gain based on the Friis transmission formula in the near-field region are reported and the validity of the new formula is checked.

1. INTRODUCTION

A new calibration method for SAR (Specific Absorption Rate) probes is required to evaluate SAR values of various mobile communication devices above 3GHz. A conventional calibration method by use of with the waveguide filled with the tissue equivalent liquid [1], [3] is widely employed in 300MHz-3GHz [1]. However, the stronger effect of the probe diameter cannot be ignored at the higher frequency, especially the diameter is comparable to the cross-sectional dimension of the waveguide above 3GHz. Therefore, an alternative calibration method have been developed by the authors [4]–[6].

In our proposed calibration, the gain of the reference antenna in the liquid [7] is evaluated by use of two antenna method based on the Friis transmission formula in the conducting medium [8]. Then, the SAR probe can be calibrated by relating the electric field radiated by the reference antenna to the output voltage of the probe at a point in the liquid [1], [2]. S parameters between two identical reference antennas which are faced and aligned with each other are measured to evaluate the gain of the reference antenna. In other words, two identical antennas are connected to port 1 and 2 of the network analyzer, and then the magnitude and phase of S_{21} between two ports are measured as a function of the distance between two antennas. Measured data are fit into curves derived from the Friis transmission formula in the far-field region and then the gain of the reference antenna, the attenuation and phase constants of the medium, α, β, can be estimated.

However, the decay in the liquid is so enormous that the measurement of S_{21} can be difficult in the far-field region [6]. For example, the attenuation constant in the liquid is $\alpha = 470$dB/m at 2.45GHz. Above 3GHz, the decay is more enormous, so that measurable range for S_{21} is much shorter than one expected by the scaling rule of the wavelength for the frequency. At the time of writing, we have tried to study the following solutions.

1) To gain the input power to the measurement system, P_{in}, amplifiers can be inserted in former stages of port 1 of the network analyzer.
2) To ensure wide dynamic range of the measurement system, the magnitude of S_{21} can be measured as a function of the distance between the antennas by use of a spectrum analyzer instead of a network analyzer. Since the phase of S_{21} cannot be measured by use of the spectrum analyzer, the permittivity of the liquid is required to be measured by the contact probe method.
3) To avoid the curve fitting in the far-field region, measured S_{21} should be fitted into the curves based on the Friis transmission formula which holds in the near-field region of the antenna in the liquid.

This paper will report some results for the item 3). The Friis transmission formula in the Fresnel region of the antennas in free space had been studied to estimate the gain of relatively large-scaled aperture antennas; the gain is represented by a function of the distance from the antenna and determined by its convergent point [13], [14]. However, no references described the behavior of the fields or the Friis transmission formula in the near-field region of the antenna in the conducting medium as far as the authors know.

In this paper, the Friis transmission formula which holds in the near-field region of the antenna in the conducting medium is proposed by abstracting some points from both the Friis transmission formula in the near-field region of the antenna in free space [14] and the Fresnel approximations in free space [15]. To discuss a physical aspect of new formula, the distance dependence of the electric field in the near-field region is examined for a dipole antenna and is extended for an arbitrary antenna. And, target functions for curve fitting are rewritten on the basis on extended Friis transmission formula in the near-field region. Finally, new curve fitting is applied to calculated and measured data to confirm the validity of the new formula.

2. Extension of Friis Transmission Formula

A. Friis Transmission Formula in the Far-Field Region

Two polarization matched antennas are aligned for maximum directional radiation in the liquid, as shown Fig. 1. If the distance between two antennas, r, is sufficiently large, the ratio of transmitted power, P_1, to received power, P_2, based on the Friis transmission formula in the far-field region [8], can be expressed by

$$|S_{21}|^2 = \frac{P_2}{P_1} = (1-|S_{11}|^2)(1-|S_{22}|^2)\frac{|G_1||G_2|e^{-2\alpha r}}{4\beta^2 r^2}, \quad (1)$$

where S_{ij} are S parameters between the ports of two antennas, $|G_i|$ are the magnitude of the gain of antenna i, and α and β denote the attenuation and phase constants in the liquid, respectively. The subscript i means the transmitting or receiving antennas for $i = 1$ or 2. (1) can be rewritten in dB form as

$$|S_{21}|_{\text{dB}} = A - 20\log_{10} r - 8.686\alpha r. \quad (2)$$

$|S_{21}|_{\text{dB}}$ can be measured as a function of the distance r and a constant A and the attenuation constant α can be determined by the curve fitting for $|S_{21}|_{\text{dB}}$ based on (2). Then, the sum of the gains in dB form can be expressed by

$$(G_1)_{\text{dB}} + (G_2)_{\text{dB}} = A + 20\log_{10}(2\beta) - (M_1)_{\text{dB}} - (M_2)_{\text{dB}}, \quad (3)$$

where $(M_i)_{\text{dB}} = 10\log_{10}(1-|S_{ii}|^2)$ is a mismatch or reflection efficiency of antenna i. If two antennas are identical, their gains are equal. Then, (3) can be replaced by

$$G_{\text{dB}} = \frac{1}{2}\left[A + 20\log_{10}(2\beta) - (M_1)_{\text{dB}} - (M_2)_{\text{dB}}\right]. \quad (4)$$

In the conventional two-antenna method, the constant A or the gain G_{dB} can be determined at a distance, r, in accordance with (2) or (4). On the other hand, our method is more accurate than the conventional one because A is determined by use of the curve fitting. However, the phase constant β in the liquid is required to evaluate the gain in accordance with (4). The phase constant can be also determined by the contact probe method. However, the phase constant β is determined by measuring $\angle S_{21}$ as a function of the distance r in our method. When the wave travels in the liquid, phase shift is expressed by a linear function of the distance r as follows:

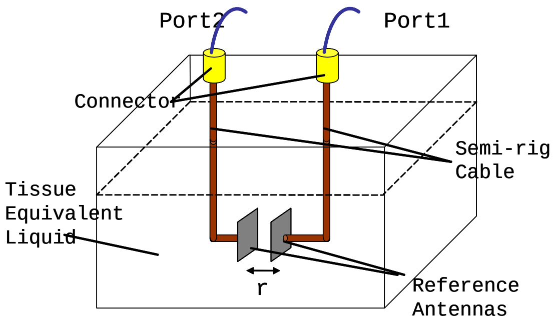

Fig. 1: A measurement system for the gain of the antenna in the liquid.

$$\angle S_{21} = -\beta r + B, \quad (5)$$

where $B = (\angle G_1 + \angle G_2)/2$ is a mean value of fictitious phases of the gains of two antennas. $\angle S_{21}$ can be measured as a function of the distance r, then the phase constant β can be determined by the curve fitting for $\angle S_{21}$ based on (5). The above curve fitting can be performed without initial values in using the linear least-square method.

Now, the following equation can be obtained by combining (1) and (5):

$$S_{21}^2 = (1-|S_{11}|^2)(1-|S_{22}|^2)\frac{G_1 G_2 e^{-2\gamma r}}{4\beta^2 r^2}, \quad (6)$$

where $\gamma = \alpha + j\beta$ is the propagation constant in the liquid and $G_i = |G_i|\exp(j\angle G_i)$ can be viewed as complex gain of antenna i. Thus, the distance dependence of S_{21} between antennas can be expressed by

$$f(r) = \frac{e^{-\gamma r}}{r}. \quad (7)$$

The above expression is identical to the distance dependence of the electric field when the transmitting antenna is a point source located at the origin. However, it can not be rigorously represented as the behavior of S_{21} in the near-field region of the antennas because the fields in that region depend on the dimension of the antenna.

B. Fresnel Approximations in the Conducting Medium

In general, an antenna can be viewed as the superposition of point sources. For example, we consider two dipole antennas with a length of $2l$, which are faced and aligned with each other. If the distance between two antennas is denoted as r, the distance between the middle point of a dipole and the end of the other can be expressed as $R = \sqrt{r^2 + l^2}$. If two dipole antennas are much closer, i.e. $l/r \ll 1$, R can be approximated as follows:

$$R = r\sqrt{1+\left(\frac{l}{r}\right)^2} \approx r\left\{1+\frac{1}{2}\left(\frac{l}{r}\right)^2\right\} = r + \frac{l^2}{2}\frac{1}{r}. \quad (8)$$

Thus, the distance R between arbitrary points on two antennas may include the contribution of $1/r$ as well as r. The term of $1/r$ dominantly contributes to R or the behavior of the fields as r is closer to zero.

To derive a general expression, we consider the case that the current distribution of the transmitting antenna is expressed as $\mathbf{J}(\mathbf{r})$. Then, the electric field in the center of the receiving antenna $\mathbf{E}(\mathbf{r})$ is given by [16]

$$\mathbf{E}(\mathbf{r}) = -j\omega\mu\left[\bar{\mathbf{I}} - \frac{1}{\gamma^2}\nabla\nabla\right]\cdot\iiint_v \mathbf{J}(\mathbf{r}')\frac{e^{-\gamma|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}dv', \quad (9)$$

where $\mathbf{r}$ and $\mathbf{r}'$ denote the position vectors on the transmitting antenna and at the center of the receiving antenna, respectively. And $\bar{\mathbf{I}}$ denotes unit dyad. For the Fresnel approximations, the distance between two points R can be approximated by

$$\begin{aligned} R = |\mathbf{r}-\mathbf{r}'| &\approx r - \hat{\mathbf{r}}\cdot\mathbf{r}' + \frac{r'^2 - (\hat{\mathbf{r}}\cdot\mathbf{r}')^2}{2r} \\ &= r - \hat{\mathbf{r}}\cdot\mathbf{r}' + \frac{a_1(\mathbf{r}')}{r}, \end{aligned} \quad (10)$$

where $r = |\mathbf{r}|$, $\hat{\mathbf{r}} = \mathbf{r}/r$, $r' = |\mathbf{r}'|$, and $a_1(\mathbf{r}') = \{r'^2 - (\hat{\mathbf{r}}\cdot\mathbf{r}')^2\}/2$. As is well known, for the far-field approximations, R in the denominator of the integrand in (9) can be approximated by $R \approx r$ and R in the exponential term $e^{-\gamma R}$ in (9) can be approximated by $R = r - \hat{\mathbf{r}}\cdot\mathbf{r}'$. Therefore, the far-field approximation of (9) can be given by

$$\mathbf{E}^{\text{far}} = -j\omega\mu\left[\bar{\mathbf{I}} - \frac{1}{\gamma^2}\nabla\nabla\right]\cdot\frac{e^{-\gamma r}}{4\pi r}\iiint_v \mathbf{J}(\mathbf{r}')e^{\gamma\hat{\mathbf{r}}\cdot\mathbf{r}'}dv'. \quad (11)$$

The above expression includes the propagation factor, $e^{-\gamma r}$, and the far-field term of the spatial spreading factor, $1/r$.

Then, we consider the electric field $\mathbf{E}$ for the Fresnel approximations. If a constant b_1 which is satisfied with the following equation exists

$$\iiint_v \mathbf{J}(\mathbf{r}')e^{\gamma\hat{\mathbf{r}}\cdot\mathbf{r}' - a_1(\mathbf{r}')/r}dv' = e^{-b_1/r}\iiint_v \mathbf{J}(\mathbf{r}')e^{\gamma\hat{\mathbf{r}}\cdot\mathbf{r}'}dv', \quad (12)$$

(9) can be approximated as follows:

$$\mathbf{E}^{\text{near}} = -j\omega\mu\left[\bar{\mathbf{I}} - \frac{1}{\gamma^2}\nabla\nabla\right]\cdot\frac{e^{-\gamma r - b_1/r}}{4\pi r}\iiint_v \mathbf{J}(\mathbf{r}')e^{\gamma\hat{\mathbf{r}}\cdot\mathbf{r}'}dv'. \quad (13)$$

(13) includes the propagation factor, $e^{-\gamma r}$, and the far-field term of the spatial spreading factor, $1/r$, as is the case for the far-field approximations. In addition, the electric field $\mathbf{E}$ includes the factor $e^{-b_1/r}$ which takes on a unique characteristic of the Fresnel approximation. If $\text{Re}(b_1) > 0$, the magnitude of the electric field becomes smaller as r is closer to zero, because of the existence of the factor $e^{-b_1/r}$. Moreover, the Fresnel term of the spatial spreading factor, $1/r^2$, contributes to the fields if r is closer to zero. As mentioned above, for the Fresnel approximations, the distance dependence of S_{21} between the antennas should be extracted as

$$f(r) = \frac{e^{-\gamma r}}{r}e^{-b_1/r}\left(1+\frac{c_1}{r}\right). \quad (14)$$

By adding a term of the inverse square of the distance, c_2/r^2, the factor $(1 + c_1/r)$ in (14) could be replaced by $(1 + c_1/r + c_2/r^2)$. Thus, this asymptotic expansion corresponds to the Friis transmission formula in the near-field region of the antenna in the lossless medium, especially, free space [14]. Although the added term c_2/r^2 corresponds to the behavior of the fields in the reactive near-field region of the antenna, the measurement in this region is practically impossible because extremely smaller r can not be assigned in our measurement system. And the term c_1/r corresponds to the behavior of the Fresnel fields so that its contribution cannot be ignored in the measurable range of our system. On the other hand, the factor $e^{-b_1/r}$ is exposed by the Fresnel approximation of the exponential term in (9). In the Fresnel approximations in free space, the phase near the antenna is shifted by the contribution of the distance dependence of $1/r$ as well as r [15]. In addition, as discussed above, not only phase shift but also exponentially decay are included in the electric field in the near-field region of the antenna in the conducting medium.

C. Friis Transmission Formula in the Near-Field Region

As expected from (14), S_{21}^{near} in the near-field region can be related to S_{21} in the far-field region as follows:

$$\begin{aligned} (S_{21}^{\text{near}})^2 &= S_{21}^2 \cdot e^{-2b_1/r}\left(1+\frac{c_1}{r}\right)^2 \\ &= (1-|S_{11}|^2)(1-|S_{22}|^2)\frac{G_1G_2e^{-2\gamma r}}{4\beta^2r^2} \\ &\quad \cdot e^{-2b_1/r}\left(1+\frac{c_1}{r}\right)^2. \end{aligned} \quad (15)$$

Thus, the distance dependence of $|S_{21}|_{\text{dB}}$ in the near-field region can be replaced by

$$\begin{aligned} |S_{21}^{\text{near}}|_{\text{dB}} &= A - 20\log_{10} r - 8.686\alpha r \\ &\quad + \frac{A_1}{r} + 10\log_{10}\left|1+\frac{A_2}{r}\right|, \end{aligned} \quad (16)$$

where A_1 and A_2 are constants. $|S_{21}|_{\text{dB}}$ can be measured as a function of the distance r, and then A, α, A_1 and A_2 can be determined by curve fitting for $|S_{21}|_{\text{dB}}$ based on (16). The sum of gains in dB form of two antennas is given by (3) as before. Similarly, the distance dependence of $\angle S_{21}$ in the near-field region can be replaced by

$$\angle S_{21}^{\text{near}} = -\beta r + B + \frac{B_1}{r}, \quad (17)$$

where B_1 is constant. $\angle S_{21}$ can be measured as a function of the distance r, and then β, B and B_1 can be determined by curve fitting for $\angle S_{21}$ based on (17).

The above curve fittings in the near-field region must be employed by a nonlinear least square method, which is often sensitive to its initialization.

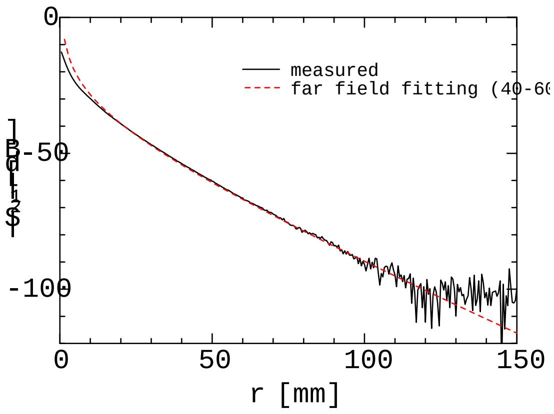

Fig. 2: Measured $|S_{21}|_{\rm dB}$ and its curve fitting based on the Friis transmission formula in the far-field region.

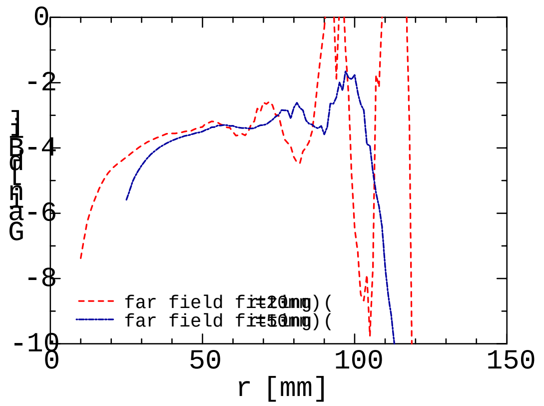

Fig. 3: Estimated gain by curve fitting for measured S_{21} based on the Friis transmission formula in the far-field region.

3. Curve Fitting Based on Friis Transmission Formula in the Near-Field Region

A. Far Field Fitting for Measured Data

The conducting medium assumed in this paper is the tissue equivalent liquid for SAR estimation [1], [3] at 2.45GHz. The liquid has a permittivity of 39.2 and conductivity of 1.84S/m at 22°C, which are measured by the contact probe method.

Next, we discuss the measurable range and level by measuring $|S_{21}|$ between two dipole antennas, which are faced and aligned with each other. The length of the dipole antenna is 13mm, which corresponds to a half of the wavelength in the liquid. Fig. 2 shows the measured $|S_{21}|$ as a function of the distance r. The output power level of a network analyzer (Agilent N5230A) is set up as -5dBm. The attenuation is mainly caused by conducting loss in the liquid as well as insertion loss in the RF cables. As shown in Fig. 2, the measured data hardly fluctuate at $r = 70$mm, however, they largely do at $r = 100$mm. This is because the noise level is smaller than the signal level at $r = 70$mm and is not at $r = 100$mm. For reference, the values of $|S_{21}|$ are about -70dB and -90dB at $r = 70$mm and 100mm, respectively.

Fig. 3 shows the estimated gain of the dipole antenna in the liquid determined by the curve fitting for the measured S_{21} based on the Friis transmission formula in the far-field region, which is abbreviated to far-field fitting in this paper. The horizontal axis in this graph r_c denotes the center of the fitting range $[r_c - \Delta r, r_c + \Delta r]$, where Δr denotes the width of the fitting range. For simplicity, r_c is typed as r in this figure. As expected, the estimated gain with no fluctuation can be obtained up to $r = 70$mm for the cases of both $\Delta r = 20$mm and 50mm, and then it is noisier as r is larger, and the gain can not be estimated when $r \geq 100$mm. Therefore, the gain should be estimated by using measured data up to $r = 70$mm. However, as shown in Fig. 3, the estimated gain at $r = 70$mm does not converge with the ideal gain in the far-field region. Therefore, as described before, a strong solution is required to overcome the difficulty that the measurement is impossible in the far-field region due to the large decay in the liquid.

B. Fresnel Field Fitting for Calculated Data

Measurement of S parameters between two center-fed half-wavelength dipole antennas which are faced and aligned with each other in the liquid can be simulated by the methods of moment for the thin-wire structure in the conducting medium coded by Richmond [4], [17]. The code can output the performance of the antenna, the characteristics of wave propagation and the coupling effect between antennas in the liquid. In addition, it can calculate them in extremely short time, in contrast with the large-scaled numerical computations, for example, FDTD. The short-time calculation is attractive in simulating the gain calibration which is required to plot the field at many points. Of course, this code simulates S_{21} with no noise so that we can determine the minimum distance r_c that the curve fitting is valid in the far-field region.

Now, we present an example of the curve fitting for the calculated data at 2.45GHz based on the Friis transmission formula in the near-field region, which is abbreviated to Fresnel field fitting in this paper. A built-in function of a spreadsheet software is used as a nonlinear least square method. The curve fitting is performed in the range of [20mm, 60mm]. Then, the permittivity and conductivity in the liquid is estimated to be 39.15 and 1.80S/m, which are almost equal to their preset values. The estimated gain is -0.35dBi, which is equal to the gain obtained by the code developed by Richmond. Another estimated gain obtained by the far field fitting is -0.56dBi, which is slightly lower than the true value of the gain.

Fig. 4 shows the calculated $|S_{21}|$ and corresponding Fresnel field fitting curve as a function of r. Both curves in Fig. 4 are good agreement with each other for $r \geq 10$mm. Fig. 5 shows the estimated gain defined by (4) and (16), which is abbreviated to near-field gain, of the dipole antenna in the liquid determined by the Fresnel field fitting for the calculated S_{21}. Also, Fig. 5 shows another estimated gain determined by

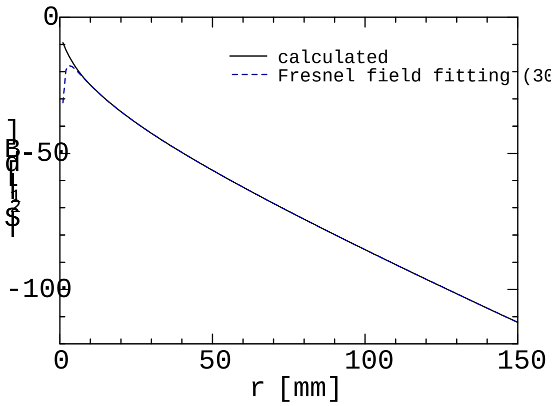

Fig. 4: Calculated $|S_{21}|$ and its curve fitting based on the Friis transmission formula in the near-field region.

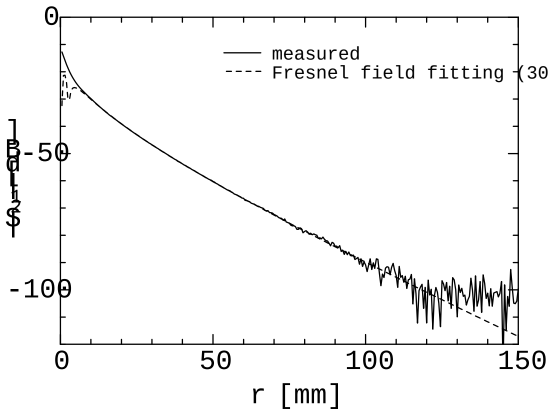

Fig. 6: Measured $|S_{21}|$ and its curve fitting based on the Friis transmission formula in the near-field region.

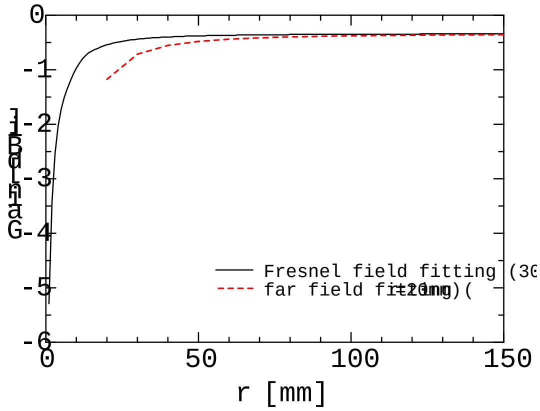

Fig. 5: Estimated gain of center-fed dipole antenna by curve fitting for calculated S_{21} based on the Friis transmission formula in the near-field region.

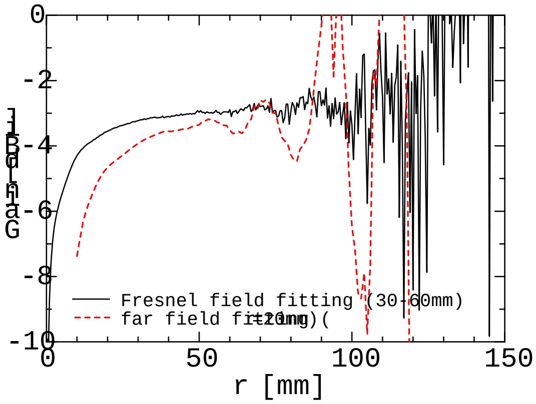

Fig. 7: Estimated gain of offset-fed dipole antenna by curve fitting for measured S_{21} based on the Friis transmission formula in the near-field region.

the far field fitting for $\Delta r = 20$mm, which is abbreviated to far-field gain. The near-field gain estimated by using the data near the antenna converges with the far-field gain. This suggests that the gain can be estimated by fitting the measured data near the transmitting antenna to the Friis transmission formula in the near-field region. The estimated gains are good agreement with the gain calculated by the methods of moment. And it is found that the wider range is required for the far-field gain to converge as shown in Fig. 5. Concretely, the far-field gain does not converge at $r = 70$mm, but it does at $r = 100$mm. The level drops by 20dB for $|S_{21}|$ measurement as the observation is moved from $r = 70$mm to 100mm. In practice, the level at $r = 100$mm is as large as the noise floor level in the measurement system. This is one of serious problem to be solved when implementing our proposed calibration.

C. Fresnel Field Fitting for Measured Data

S parameters between two identical antennas which are faced and aligned with each other in the liquid are measured and then are fit to the curves in the Fresnel field fitting. For matching, the half-wavelength dipole antenna is offset fed, that is, its arms are 1mm and 12mm long. The Fresnel field fitting is performed in the range of [30mm, 60mm]. Fig. 6 shows the measured $|S_{21}|$ and corresponding Fresnel field fitting curve as a function of r. The estimated fitting curve is not identical to measured data for $r \leq 10$mm. This is because the contribution of extremely near-field field with distance dependency of $1/r^3$ is larger than the contribution of Fresnel field with distance dependency of $1/r^2$. The fluctuation is observed in the data for $r \geq 100$mm as before.

Fig. 7 shows the near-field gain and the far-field gain for $\Delta r = 20$mm. In the same manner as fitting for the calculated data, the near-field gain converges with the far-field gain even if the curve fitting is performed by the measured data in the near-field region. As shown in Fig. 7, the near-field gain seems to converge at $r = 50$mm. However, the far-field gain does not converge at $r = 50$mm and the fluctuation is observed in the data for $r \geq 70$mm. The far-field gain suffers from the influence of the noise floor of the measurement system before it converges so that the true gain can not be obtained by the far-field gain estimation. Thus, the problem that a measurement in the far-field region is impossible due to the large attenuation in the liquid is broken down by the Fresnel field fitting in the near-field region, and then the gain can be accurately estimated. For reference, the permittivity and conductivity of the liquid are estimated to be 37.14 and 1.80S/m, respectively. And the estimated near-field gain is -2.66dBi.

4. Conclusion

A SAR probe calibration method above 3GHz discussed in this paper can be performed by calibrating the gain of reference antenna in tissue equivalent liquid and relating the output voltage of the probe to the value of the electromagnetic fields or SAR. To implement this calibration, it is required to overcome the problem that the measurement in the far-field region is made impossible to estimate the gain because of large attenuation in the liquid. As one of the solutions, we propose the method of estimating the gain of the reference antenna in the liquid after curve fitting for the measured data based on the extended Friis transmitting formula in the near-field region of the antenna in the conducting medium. The proposed method is applied to both the calculated and measured data and then its validity is demonstrated.

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