Measurement Guideline of Fresnel-Field Antenna Measurement Method

Soon-Soo Oh and Jung-Ick Moon

ABSTRACT— In this letter, a parametric analysis of the Fresnel-field antenna measurement method is performed for a square aperture. As a result, the optimum number of Fresnel fields for one far-field point is guided as $M_{opt}=N_{opt}=D^2/\lambda R+5$, where D is the antenna diameter, λ is the wavelength, and R is the distance between the source antenna and the antenna under test. For the aperture size $5 \le L_x/\lambda \le 20$, the tolerable distances for gain errors of 0.5 dB and 0.2 dB can be guided as $R_{0.5\ dB} \approx 1.2L_x/\lambda$ and $R_{0.2\ dB} \approx 2.0L_x/\lambda$, where L_x is the lateral length of the square aperture. The tolerable distances for $20 \le L_x/\lambda \le 200$ are also proposed. This measurement guideline can be fully utilized when performing the Fresnel-field antenna measurement method.

Keywords—Antenna measurement, Fresnel field, Fresnel region.

I. Introduction

Utilizing the far-field measurement system, the far-field radiation pattern and gain are measured when the source antenna and antenna under test (AUT) are fully separated satisfying Rayleigh's far-field criterion, $D_{far} \ge 2D^2/\lambda$, where D is the diameter of the radiating aperture, and λ is a free-space wavelength [1]. If Rayleigh's criterion cannot be satisfied, the AUT is placed in the Fresnel region, and the measured gain and pattern are inaccurate.

Over the past two decades, the Fresnel-field measurement technique utilizing the far-field measurement system has been studied [1]-[7]. The measured Fresnel fields are transformed into far fields by summation and production with the appropriate coefficient. The one-dimensional transform method for a linear antenna or a circular aperture having a radially uniform current distribution was proposed in [1] to [4]. The two-dimensional transform method for any type of antenna was also developed in [5]. The scanning method proposed in [5] can be called an α-variation method. More scanning methods, such as the height-variation method [6] and ϕ-variation method [7] were proposed for the mechanical configuration of the pre-owned far-field measurement system. In this letter, the two most important parameters of the Fresnel-field antenna measurement method are analyzed, and a very practical guideline is proposed for the first time, to best of our knowledge.

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II. Measurement Guideline

1. Theory of Fresnel-Field Antenna Measurement Method

The E-field in the far-field is related to the Fresnel region of distance R with the relation equation given in [5]:

$$E_{far}(\alpha,\beta) = \sum_{m=-M}^{+M} \sum_{n=-N}^{+N} k_{mn} E_R(\alpha + m\Delta\alpha, \beta + n\Delta\beta), \quad (1)$$

where L_x and L_y are its lateral length; α and β are the angles from the y-z plane and x-z plane, respectively; $\Delta\alpha=\lambda/L_x$, and $\Delta\beta=\lambda/L_y$.

Fourier coefficient k_{mn} is given as

$$k_{mn} = \frac{1}{L_x L_y} \int_{-L_x/2}^{+L_x/2} e^{+ic^2u^2} e^{-i\frac{2\pi}{L_x}mu} du \int_{-L_y/2}^{+L_y/2} e^{+ic^2v^2} e^{-i\frac{2\pi}{L_y}mv} dv, \quad (2)$$

where $c^2=\pi/\lambda R$.

2. Optimum Number of Fresnel Fields

It is obvious that the accuracy increases as more Fresnel-field

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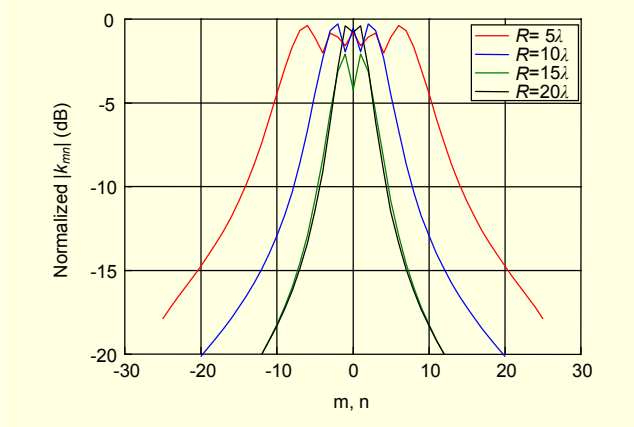

Fig. 1. Normalized $|k_{mn}|$ for $L_x = L_y = 10\lambda$.

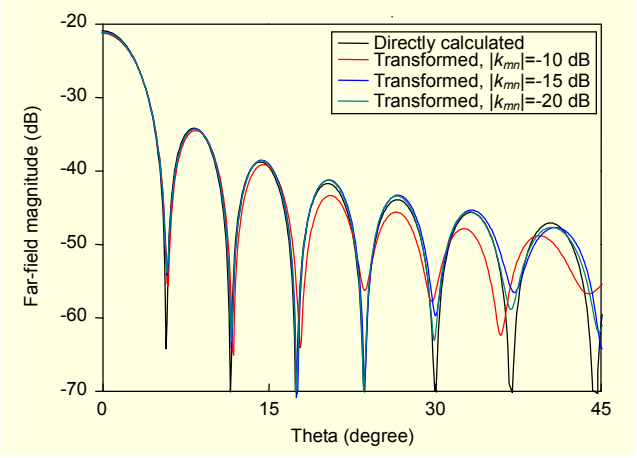

Fig. 2. Directly calculated far-field pattern and transformed far-field pattern for the normalized $|k_{mn}|$ of -10, -15, and -20 dB.

data is used for transforming, but at the same time, the scanning and transforming time increase. One important fact is that the accuracy does not increase any more for a specific amount of Fresnel-field data. Therefore, a compromise between accuracy and time could exist, and the optimum number of Fresnel fields could be guided accordingly. This is similar to the Nyquist-Shannon sampling theorem in signal processing.

Previously, the minimum number of Fresnel fields for one point of the far field was suggested in [5] as $M_{\min}=(2M+1)=D^2/\lambda R+1$, and $N_{\min}=(2N+1)=D^2/\lambda R+1$. However, from our simulations and experiments, $M_{\min}$ and $N_{\min}$ were not sufficient, so the transformed patterns were not very accurate. Another approach was proposed in [6]. The normalized magnitude of k_{mn} is plotted as shown in Fig. 1. Here, the dimension of the square aperture length is $L_x=L_y=10\lambda$, so $D=\sqrt{(L_x^2+L_y^2)}=10\sqrt{2}\lambda$. After plotting $|k_{mn}|$, M and N are selected when $|k_{mn}|$ drops by more than 15 dB from its highest value.

The reason for selecting the value of 15 dB can be found in Fig. 2. The dimension of the square aperture are $L_x=L_y=10\lambda$, and $R=20\lambda$. The corresponding $(2M+1)$ and $(2N+1)$ are 9, 15, and 25 for the normalized $|k_{mn}|$ = -10, -15, and -20 dB, respectively. As shown in Fig. 2, the transformed far-field with normalized $|k_{mn}|$ = -10 dB does not agree to the directly-calculated far-field. Although the pattern for the normalized $|k_{mn}|$ = -20 dB shows better agreement, the pattern for normalized $|k_{mn}|$ = -15 dB shows sufficient accuracy.

In this letter, we propose a simple equation based on both approaches. As shown in Fig. 1, the optimum numbers are $M_{opt}=N_{opt}$= 45, 25, 19, and 15 for $R=5\lambda$, 10λ, 15λ, and 20λ, respectively. These numbers are used in the following equations:

$$M_{opt}=(2M+1)=D^2/\lambda R+5,$$
$$N_{opt}=(2N+1)=D^2/\lambda R+5. \quad (3)$$

We also investigated $|k_{mn}|$ for $L_x=5\lambda$ and 20λ and verified (3). In some cases, (3) produces a larger number than the results obtained by plotting normalized $|k_{mn}|$, but it never generates a smaller number. Therefore, (3) is a sufficient condition.

In (3), the current distribution of the radiating aperture is not considered. The uniform current distribution keeps (3) the same. The cosine and cosine-squared distribution have smaller edge currents and smaller sidelobes; therefore, a smaller number of Fresnel fields than (3) is sufficient for higher accuracy. However, since it is difficult to find out the exact current distribution of the fabricated antenna, it is recommended to use (3).

3. Distance between Source Antenna and AUT

When applying the Fresnel-field antenna measurement method, we also consider the maximum tolerable distance from the source antenna to the AUT. For parametric analysis, we calculated the Fresnel-field pattern from (1) in [6], and transformed it into a far-field pattern by applying (1) in this study. A reference far-field pattern was also derived from (3) in [6]. The square aperture of $L_x=L_y=5\lambda$, 10λ, 20λ, 50λ, 100λ, 150λ, and 200λ was simulated at several distances of R. The current distribution was assumed to be uniform. The cosine current distribution was also simulated. The gain errors between the transformed far field and reference far field at a boresight angle were compared and are shown in Figs. 3(a) and (b) for the uniform and cosine current distributions, respectively.

As shown in Fig. 3, the gain error at the electrical distance R increases as the electrical size of the aperture increases. For example, the gain error at $R=2\lambda$, as shown in Fig. 3(a), is 0.17 dB for $L_x=10\lambda$, but 0.94 dB for $L_x=20\lambda$. Also, note that as distance R increases, which means that the AUT is placed further away from the source antenna, the gain error decreases.

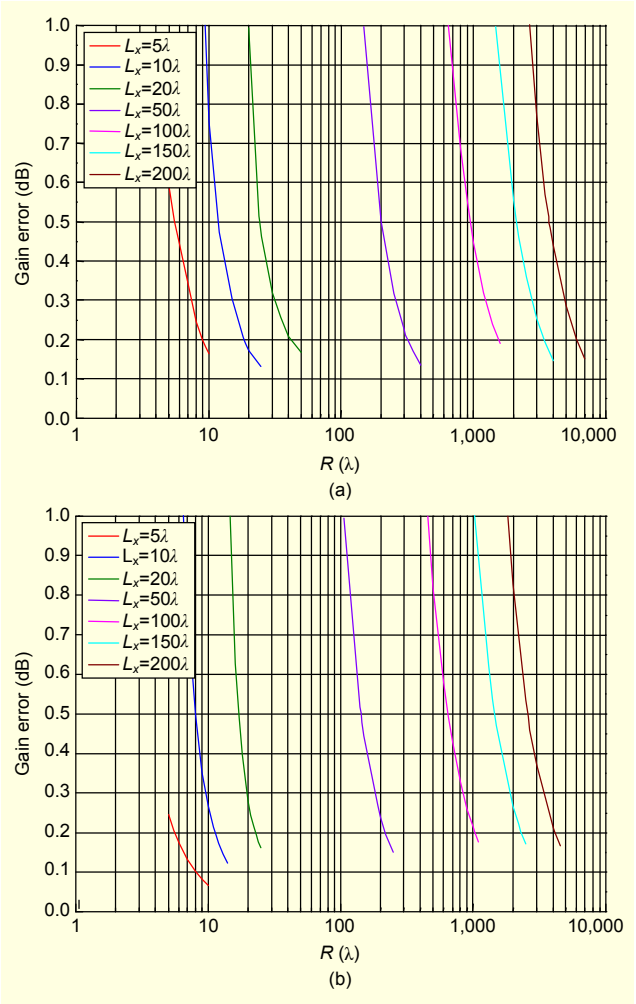

Fig. 3. Gain error versus the separation distance R: (a) uniform current distribution and (b) cosine current distribution.

Therefore, when measuring a large aperture antenna with the Fresnel-field antenna measurement method, we should carefully determine the separation distance between the source antenna and AUT.

As shown in Fig. 3(a), the gain error of 0.5 dB appears at R=5.5λ, 11.8λ, 24.2λ, 200λ, 950λ, 2100λ, and 3750λ for L_x=5λ, 10λ, 20λ, 50λ, 100λ, 150λ, and 200λ. A gain error of 0.2 dB appears at R=9λ, 18.5λ, 40λ, 320λ, 1500λ, 3500λ, and 6000λ. It should be noted that the tolerable distance increases as the aperture size increases. From the curve-fitting method, we can obtain the following polynomial equations for gain errors of 0.5 dB and 0.2 dB:

$$R_{0.5dB} \approx \begin{cases} 1.2\dfrac{L_x}{\lambda} & \text{for } 5 \le \dfrac{L_x}{\lambda} \le 20, \\ 0.092\left(\dfrac{L_x}{\lambda}\right)^2 + 0.43\dfrac{L_x}{\lambda} - 22.5 & \text{for } 20 < \dfrac{L_x}{\lambda} \le 200, \end{cases}$$

(4)

$$R_{0.2dB} \approx \begin{cases} 2.0\dfrac{L_x}{\lambda} & \text{for } 5 \le \dfrac{L_x}{\lambda} \le 20, \\ 0.14\left(\dfrac{L_x}{\lambda}\right)^2 + 2.50\dfrac{L_x}{\lambda} - 60.0 & \text{for } 20 < \dfrac{L_x}{\lambda} \le 200. \end{cases}$$

(5)

To model the curve exactly, the equations are formulated for two groups of aperture sizes.

A similar analysis was done for a cosine current distribution as shown in Fig. 3(b), and we simulated the cosine-squared current distribution. Note that the tolerable distance R for the cosine-squared current distribution is the smallest. However, because it is difficult to find the exact current distribution of the fabricated antenna, the tolerable distance for the uniform current distribution described in (4) and (5) is recommended.

III. Conclusion

In this letter, the two most important parameters of the Fresnel-field measurement antenna method were analyzed, and the resultant equations were derived. The optimum number of Fresnel fields for one point of the far-field was determined. The tolerable distance R for gain errors of 0.5 dB and 0.2 dB was guided. This guideline is very useful when the Fresnel-field measurement method is applied.

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