THE COMPLEX ANTENNA FACTOR AND WAVEFORM RECONSTRUCTION

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Abstract: The complex antenna factor (CAF) introduced to measure transient electromagnetic fields or electromagnetic pulses and its applications are investigated. The equations of the three-antenna method for determining the CAF of a dipole antenna, a log-periodic dipole array antenna (LPDA), and a monopole antenna are derived. The results of the waveform reconstructions using the CAF are compared with the calculated results. The agreements show the validity of the waveform reconstruction technique.

Key words: complex antenna factor, waveform reconstruction, three-antenna method, DOA.

1. Introduction

In order to measure transient electromagnetic fields or electromagnetic pulses using an antenna, not only the magnitude, but also the phase characteristic, of the antenna must be known [1]. The complex antenna factor (CAF) is a detection characteristic of both magnitude and phase able to be used for electromagnetic waveform measurements [2].

In principle, the three-antenna method can be used to determine the CAF of an arbitrary antenna [3]. However, the equation to calculate the CAF depends on the antenna structure and the attached circuit. In this paper, the three-antenna method for dipole antenna with a balun, log-periodic dipole array antenna (LPDA), and monopole antenna are investigated, and the equations are derived. The equations are ensured by comparing the results of another methods. The results of the waveform reconstructions using the CAF are shown.

2. Complex Antenna Factor

2.1 Definition

When a dipole antenna receives a plane wave of angular frequency ω, as shown in Fig.1, the complex antenna factor (CAF) is defined as

$$F_c(\omega) = \frac{E(\omega)}{V_o(\omega)} \quad , \tag{1}$$

where $E(\omega)$ is the incident complex electric field of the plane wave with the polarization giving the maximum output, and $V_o(\omega)$ is the complex voltage of the load with the impedance Z_0 matched to the coaxial line.

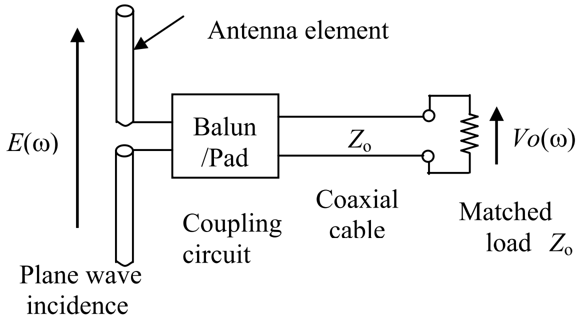

Fig.1 Complex antenna factor

Fundamentally, the CAF is equivalent to the reciprocal of the antenna transfer function. It should be noted that the CAF is defined for a non-reflecting load [4]. A mismatched load is not adequate for electromagnetic waveform measurements. Not only the magnitude, but also the phase of the CAF varies with the reflection coefficient of the load.

2.2 Three-antenna Method

When the CAF of a dipole antenna is measured by the usual three-antenna method, two of three dipole antennas are placed facing each other in free-space as shown in Fig.2. In this figure, R is the distance between the two antennas, η_0 is the wave impedance of free-space, and λ is the wavelength.

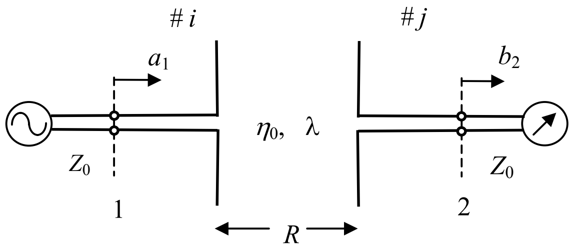

Fig.2 Three-antenna method for dipole antennas

Then, the transmission S-parameter

$$A_{ji}(R) = \left[S_{21}(R)\right]_{\#i \to \#j} \qquad (i, j = 1,2,3) \tag{2}$$

between transmitting antenna $\#i$ and receiving antenna $\#j$ is measured. The suffixes of $A(R)$ correspond to the antenna numbers. If R is satisfy the far-field condition, and the detector of the receiving antenna is matched to the two-wire feeder line, the transmission S-parameter can be expressed as

$$A_{ji}(R) = j\frac{1}{F_{ci}}\cdot\frac{1}{F_{cj}}\cdot\frac{\eta_0}{\lambda Z_0}\cdot\frac{\exp(-jkR)}{R}, \quad (3)$$

where k (=2 π/λ) is the wave number.

The three two-antenna sets yield three equations by which to calculate the CAF of each antenna in terms of $A_{ji}(R)$. For example, the CAF of antenna #1 can be obtained from

$$F_{c1}(\omega) = \sqrt{\frac{j\eta_0 A_{32}(R)}{\lambda Z_0 A_{21}(R) A_{13}(R)}\cdot\frac{e^{-jkR}}{R}} . \quad (4)$$

This is the basic equation to calculate CAF by the far-field three-antenna method.

2.3 Intrinsic Phase Ambiguity

The three-antenna method cannot determine the phase of CAF completely. The equation (3) is a function of the product $F_{ci}F_{cj}$ so that -F_{c1} is also an alternative solution to (4). The polarity has to be determined from additional information or by comparing a result of another method at an adequate frequency.

Besides, the phase is calculated only in $-\pi/2$ to $\pi/2$, because of the root in the right hand side of (4). Therefore, the phase unwrapping is required [5].

2.4 Field Transfer Factor

If the two antennas are actually placed so as to satisfy the far-field condition, the transmission S-parameter can be hardly measured, because of the sensitivity problem. In order to cope with this problem, a field transfer factor (FTF) is introduced [4].

The FTF is defined as the ratio of the far-field $A_{ji}(R)$ to a near-field $A_{ji}(r)$, and it can be approximated as

$$q(r,R) = \frac{A_{ji}(R)}{A_{ji}(r)} \cong \frac{[S_{e21}(R)]_{\#i\to\#j}}{[S_{e21}(r)]_{\#i\to\#j}}, \quad (5)$$

where $S_{e21}(R)$ and $S_{e21}(r)$ is the element-to-element S-parameters at the far-field and the near field, respectively. The element-to-element S-parameters can be calculated using a numerical method, such as the method of moments, so that the far-field $A_{21}(R)$ can be estimated from the measured $A_{21}(r)$ in order to use (4). This estimation from the near-field data $A_{ji}(r)$ to the far-field value $A_{ji}(R)$ using the FTF can reduce the effects of undesired reflection from the surroundings or the effects of the ambient noise.

2.5 Waveform Reconstruction

When a transient electric field $e(t)$ is in incident on a dipole antenna as shown in Fig.3, we can reconstruct the waveform in frequency domain by inverse filtering from the output voltage $v_o(t)$ with the CAF. We call such processing as "waveform reconstruction". The processing is shown as

$$e(t) = \mathcal{F}^{-1}\left[F_c(\omega)\mathcal{F}\{v_o(t)\}\right] \quad , \quad (6)$$

where $\mathcal{F}$ and $\mathcal{F}^{1}$ denote the Fourier transform and the inverse Fourier transform, respectively.

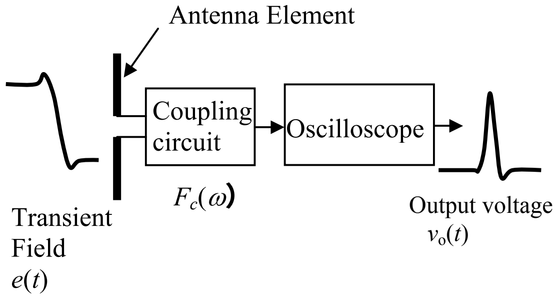

Fig.3 Waveform reconstruction

3. Dipole Antenna and LPDA

Consider the three-antenna method for determining the CAF of a dipole antenna with balun as shown in Fig.4. In this case, it should be noted that the phase of the transmission S-parameter A_{ji} is inverted compared to the transmission without the baluns.

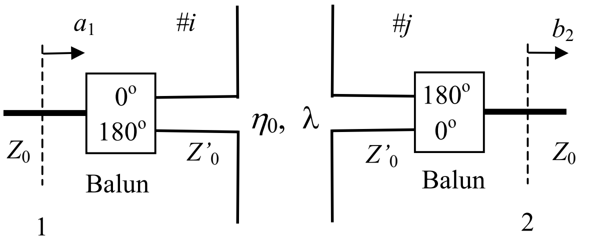

Fig.4 Transmission between two dipole antennas with balun

The three S-parameters A_{ji} in (4) must be changed to -A_{ji} , resulting in

$$F_{c1} = \sqrt{\frac{\eta_0 A_{32}(R)}{j\lambda Z_0 A_{21}(R) A_{13}(R)}\cdot\frac{e^{-jkR}}{R}} . \quad (7)$$

The same modification is necessary for LPDA as shown in Fig.5.

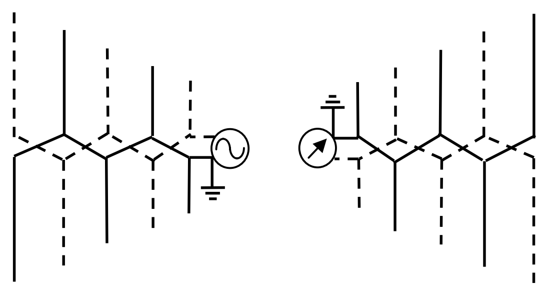

Fig.5 Transmission between two log-periodic dipole array antennas

The measured CAF of a LPDA (nominal bandwidth: 600 MHz – 2 GHz) is shown in Fig.6, where the near-field (measurement) distance r is 1 m and the far-field distance R for the FTF estimation is 100 m. The phase is unwrapped.

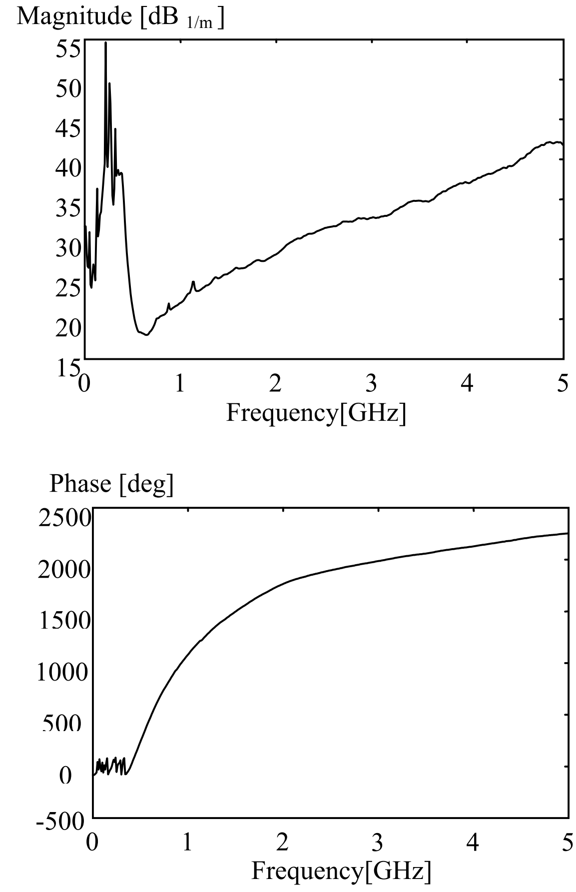

Fig.5 Measured CAF of a LPDA

Using the above CAF, an electromagnetic pulse is reconstructed. The result is shown in Fig.6 with a calculation result.

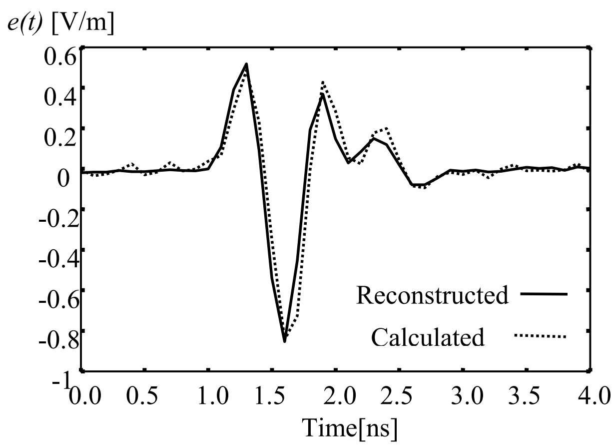

Fig.6 Reconstructed and calculated waveforms (antenna: LPDA)

In this experiment, the electromagnetic pulse is radiated from a monopole antenna (length: 3 cm) near an edge of a ground plane, and detected at a point 1m apart from the monopole. In the calculation, the uniform current distribution as a small monopole is assumed, and the effect of the edge is considered using the UTD (Uniform Theory of Diffraction) [7]. From this result, the CAF based waveform reconstruction technique has been confirmed.

4. Monopole Antenna

For the monopole-to-monopole transmission shown in Fig.7, the term in the root of (4) must be multiplied by 2 as

$$F_{c1}(\omega) = \sqrt{\frac{2j\eta_0 A_{32}(R)}{\lambda Z_0 A_{21}(R) A_{13}(R)}} \cdot \frac{e^{-jkR}}{R} , \qquad (8)$$

because of the image of the transmitting monopole.

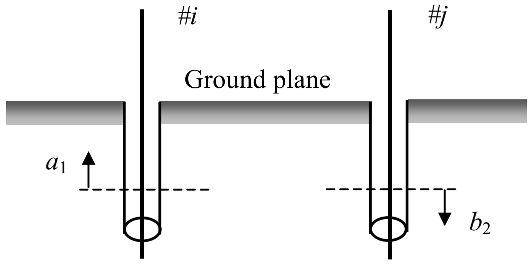

Fig.7 Transmission between two monopoles

The measured CAF of a monopole antenna (length: 1.5 cm) is shown in Fig.8, where the near-field (measurement) distance r is only 1.5 cm and the far-field distance R for the FTF estimation is 100 m. The phase is unwrapped.

Using the CAF, an electromagnetic pulse is reconstructed. The result is shown in Fig.9 with a calculation result. In this calculation, the frequency domain method of moments and Fourier transform are used. In this experiment, the electromagnetic pulse is radiated from a monopole antenna (length: 1.5 cm), and detected at a point 2 cm apart from the radiating monopole. The waveforms of reconstructed and calculated electric fields agree well both in shape and in magnitude. It should be noted that the reconstruction is done in a vicinity of the radiating antenna using the CAF for plane waves.

5. Application

The CAF depends on the direction of arrival (DOA) of an incident wave. This nature can be made good use of finding DOA. Consider an electromagnetic pulse arriving at an antenna from an unknown direction. The CAF of an antenna is measured beforehand at different angles including the DOA.

The waveform reconstructions are conducted for all the angles. Among the reconstructed waveforms, the one corresponding to the DOA is correct. However this is unknown. Hence, another antenna with a different characteristic is used, and the same waveform reconstructions are carried out using the CAF of this antenna. Then, the identical and true reconstructed waveform is obtained in the actual DOA [6].

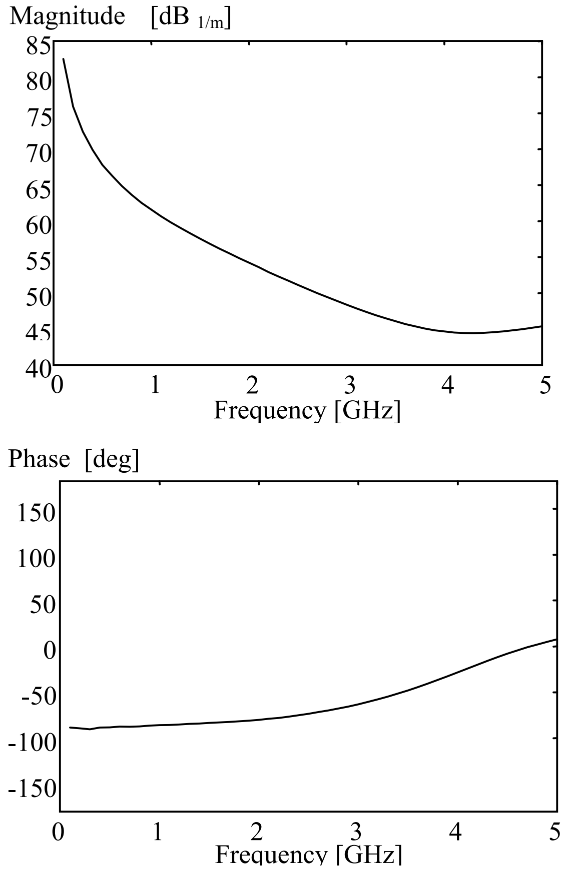

Fig.8 Measured CAF of a monopole

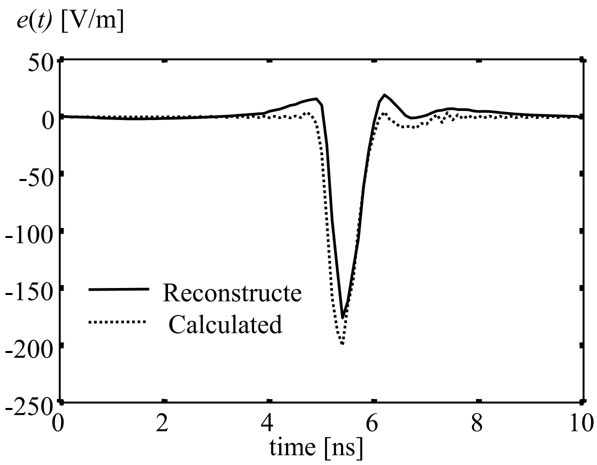

Fig.9 Reconstructed and calculated waveforms (antenna: monopole)

6. Conclusion

The complex antenna factor (CAF) has been introduced to measure transient electromagnetic fields or electromagnetic pulses. The equations of the three-antenna method for determining the CAF of a dipole antenna, a log-periodic dipole array antenna (LPDA), and a monopole antenna are shown. The results of the waveform reconstructions using the CAF are compared with the calculated results, and the agreements show the validity of the waveform reconstruction technique.

Acknowledgement

This work was supported by the Research for the Future Program, Japan Society for the Promotion of Science. The authors wish to thank Prof. Y. Kami for his encouragement.

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