A TIME–DOMAIN SUPERRESOLUTION TECHNIQUE FOR SCATTERING MEASUREMENTS

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1 Introduction

Time–domain processing based on the fast Fourier Transform (FFT) is implemented in recently developed network analyzers, and it has been widely used for many applications in electromagnetic measurements such as circuit, antenna[1], and scattering measurements. In the high–frequency scattering measurements, we can consider that the total scattered field consists of several localized mechanisms. Using the time–domain processing, we can resolve individual scattering centers in the time–domain presentation. Furthermore, each scattering mechanism can be isolated by applying the time–domain gating[2]. Then, the technique is expected to be useful for target recognition. Moreover, the measured results of scattering mechanisms can provide available information for the progress of high–frequency RCS prediction techniques (*ex.* GTD, UTD). However, the response resolution of the FFT essentially depends on a bandwidth of swept frequency data. Thus, the difficulty arises in applying the technique when the bandwidth is not wide enough for resolving the closely spaced scattering centers. The authors have proposed a superresolution time–domain technique[3] based on a MUSIC algorithm[4] to overcome the difficulty. In this paper, we show the experimental results of scattering center estimation using the MUSIC algorithm. The generalized matrix formula of the scattering mechanism extraction method[5] is also presented.

2 Problem formulation

In the high–frequency scattering problem, the total scattered field appears to emanate from a finite number of discrete sources. Here, we assume that the total scattered field consists of d discrete sources. The scattering center of each source can be expressed as t_k (k=1∼d) in the time–domain presentation. t_k denotes a delay time of the kth scattering center. Using matrix formulations, N uniformly sampled frequency–domain data $(f_1, f_2, \cdots, f_N)$ can be written as

$$\boldsymbol{r} = \sum_{i=1}^{d} \boldsymbol{A}_i \boldsymbol{s}_i + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{r}$ is the N–dimensional data vector whose kth component represents the total scattered field at frequency f_k, and $\boldsymbol{n}$ is the N–dimensional noise vector. $\boldsymbol{A}_i$ is the $N \times N$ diagonal delay parameter matrix whose (k,k)th component is $e^{-j2\pi f_k t_i}$. The reflection/diffraction coefficient of each source is expressed as the N-dimensional vector $\boldsymbol{s}_i$ in (1).

3 Time–domain superresolution technique

The estimation procedure is divided into two parts. First, we estimate the scattering centers $(t_1, t_2, \cdots, t_d)$ of individual scattering mechanisms. Extraction of the reflection/diffraction coefficients of them using scattering center information is next step. The following is the outline of the methods.

Scattering center estimation The MUSIC algorithm preprocessed by a spatial smoothing technique (MUSIC–SSP) is employed here. As reported in [3], the algorithm has superior capability of resolving signals compared with the FFT technique. Strictly speaking, the algorithm requires the frequency invariability of each reflection/diffraction coefficient. However, the simulation results show that it still possesses the highly resolution capability even when there exist frequency dependent signals such as a creeping wave[6]. In the scattering center estimation procedure, the problem is to estimate the "mode vector $\boldsymbol{a}(t_i)$" of each scattered element. Note that this mode vector corresponds to the diagonal elements of $\boldsymbol{A}_i$. The MUSIC–SSP utilizes the eigenstructure of the spatial smoothed data correlation matrix. Scattering center of each signal is estimated by searching the peak position of the following function :

$$P_{music}(t) = \frac{\boldsymbol{a}(t)^H \boldsymbol{a}(t)}{\boldsymbol{a}(t)^H \boldsymbol{E}_N \boldsymbol{E}_N^H \boldsymbol{a}(t)} \tag{2}$$

where ^{H} denotes complex conjugate transpose, and $N \times (N - d)$ matrix $\boldsymbol{E}_N$, whose column vectors are the eigenvectors corresponding to the minimum eigenvalues of the spatial smoothed data correlation matrix, denotes so called "noise subspace"[4].

Diffraction coefficient estimation Now, we deduce the formula for extracting the individual scattering mechanisms $\boldsymbol{s}_i$ (i=1$\sim$$d$) in (1). In the time–domain presentation, it is clear that each signal energy concentrates almost around the delay time t_k ($k = 1 \sim d$). Then, it is obvious that the notch filter which has deep nulls at $t_k (k \neq i)$ can remove the effects of the scattering mechanisms other than the ith one, and then extracts only the ith mechanism. For the simplicity, we shift the delay time reference of $\boldsymbol{r}$ and $\boldsymbol{a}(t)$ in the following formulations so as to become t_i=0sec. From projection theorem, such filtering matrix can be given by

$$\boldsymbol{P}_i = \boldsymbol{I} - \tilde{\boldsymbol{A}}_i (\tilde{\boldsymbol{A}}_i^H \tilde{\boldsymbol{A}}_i)^{-1} \tilde{\boldsymbol{A}}_i^H \tag{3a}$$

$$\tilde{\boldsymbol{A}}_i = [\boldsymbol{a}(t_1), \boldsymbol{a}(t_2), \cdots, \boldsymbol{a}(t_{i-1}), \boldsymbol{a}(t_{i+1}), \cdots, \boldsymbol{a}(t_d)] \tag{3b}$$

where $\boldsymbol{I}$ is an identity matrix. Carrying out the multiplication of the data vector $\boldsymbol{r}$ by the filtering matrix $\boldsymbol{P}_i$, the ith mechanism is extracted.

$$\boldsymbol{P}_i \boldsymbol{r} \simeq \boldsymbol{P}_i \boldsymbol{s}_i \tag{4}$$

Because of the singularity of $\boldsymbol{P}_i$, we cannot solve (4) for $\boldsymbol{s}_i$. Therefore, the following assumption, which corresponds to the smoothness of the frequency dependence of each mechanism, is adopted in addition to (4).

$$\boldsymbol{D} \boldsymbol{s}_i \simeq \boldsymbol{o} \tag{5}$$

where $\boldsymbol{D}$ is formed with element values which yield a second–order derivative operator[5]. Form (4) and (5), the ith scattering mechanism $\boldsymbol{s}_i$ is derived as follows :

$$\boldsymbol{s}_i = \boldsymbol{Q}_i^{-1} \boldsymbol{P}_i \boldsymbol{r} \tag{6a}$$

$$\boldsymbol{Q}_i = \boldsymbol{P}_i + \boldsymbol{D}^H \boldsymbol{D}. \tag{6b}$$

When a prior information about the frequency dependence of each signal is available, we can modify the equations, (4) and (5), including information and hence improve the estimation accuracy of (6). We may say that this is one of the generalized formula of the Ksienski's matrix method[5].

4 Experimental results

The following experiment is done with a quasi-monostatic RCS measurement system using a network analyzer (HP8510B). Transmitting/receiving antennas and target are placed in a radio anechoic chamber. The target is placed at a distance of about 3.7m from the antennas. In this experiment, we use a 101.6mmϕ metal sphere as a target. Our object in this experiment is to resolve a specular return (a geometrical optics wave) and a creeping wave of the sphere. A 85mmϕ metal sphere is used as the calibration sphere.

Fig.1 shows the calculated and measured spectra of the target sphere. The specular return and creeping wave (2$\sim$10GHz) shown in this figure are the results extracted by the FFT based time-domain technique. As you may see from this figure, the measured results coincide with the calculated ones well. The time-domain responses using the inverse-FFT (IFFT) are plotted in Fig.2. In this figure, we place t=0 at the center of the sphere. Each scattering mechanism shown in Fig.1 is the result extracted from the "8GHz span" response using the time-domain gating. As shown in Fig.2, about 4GHz bandwidth data are required to resolve these scattering centers. Moreover, to employ FFT based time-domain gating properly, nearly 8GHz bandwidth data are desired. We cannot resolve the specular and the creeping wave when the swept frequency bandwidth is less than 2GHz.

Next, we apply the superresolution technique to the 2GHz bandwidth data. Fig.3 shows the results of scattering center estimation using the MUSIC-SSP. 'M' in this figure denotes the number of subarrays[3]. These two scattering centers can be correctly resolved when 'M' exceeds 7. The frequency bandwidth for M=7 is only 1GHz. By calculating (6) using estimated scattering center information, each scattering mechanism is extracted. The results are also shown in Fig.1 (marked as "MUSIC-SSP (1GHz span)"). The RCS of the signal at the delay time 1.78nsec in Fig.2 is below 50dBsm. Then, it may be considered to be a spurious signal. The estimated result of specular return coincides well with that of the FFT based time-domain technique using the wideband (8GHz span) frequency data. Though the result of the creeping wave is slightly biased, the estimated errors are within 1.2dB.

5 Conclusions

A time-domain superresolution technique for scattering measurements has been presented. Experimental results illustrate that it has the superior capability of resolving scattering centers compared with the conventional FFT based time-domain techniques. The generalized matrix formula for scattering mechanism extraction have been also derived. The superresolution technique is expected to be useful for the time-domain scattering analysis.

References

[1] W. Briggs, "Analyzer improvements make real-time antenna tests practical", *MSN&CT*, p.74-86, May 1987.

[2] A. K. Dominek, L. Peters, Jr, and W. D. Burnside, "A time domain technique for mechanism extraction", *IEEE Trans. Antennas and Propagat.*, vol.AP–35, no.3, pp.305–312, Mar. 1987.

[3] H. Yamada, M. Ohmiya, Y. Ogawa, and K. Itoh, "Superresolution techniques for time–domain measurements with a network analyzer", *IEEE Trans. Antennas and Propagat.*, vol.39, no.2, pp.177–183, Feb. 1991.

[4] R. O. Schmidt, "Multiple emitter location and signal parameter estimation", *IEEE Trans. Antennas and Propagat.*, vol.AP–34, no.3, pp.276–280, Mar. 1986.

[5] D. A. Ksienski, "A method of resolving data into two maximally smooth components", *Proc. IEEE*, vol.73, no.1, pp.166–168, Jan. 1985.

[6] Y. Ogawa, H. Yamada, and K. Itoh, "A time–domain superresolution technique for antenna measurements and scattering studies", 1991 International IEEE/AP–S Symposium Digest, vol.2, 68.8, pp.1198–1201, June 1991.

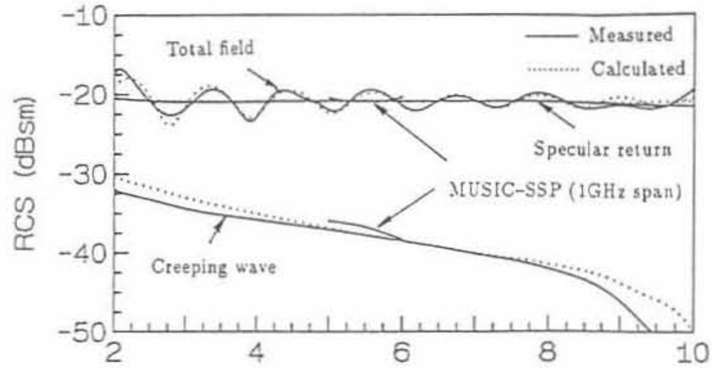

Fig.1. The backscattered total, specular, and creeping fields for a 101.6mmϕ metal sphere. MUSIC–SSP(1GHz span) denotes the extracted results by eq.(6).

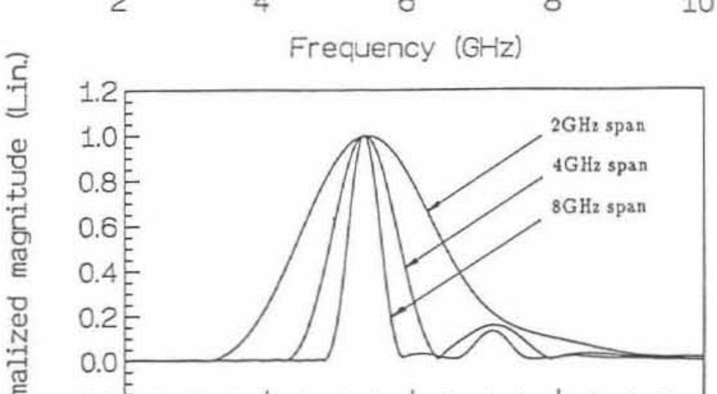

Fig.2. Time–domain responses of a 101.6mmϕ metal sphere using the inverse–FFT. 2GHz span : The swept frequency band is from 4.5GHz ~ 6.5GHz. 4GHz span : The swept frequency band is from 3.0GHz ~ 7.0GHz. 8GHz span : The swept frequency band is from 2.0GHz ~ 10.0GHz.

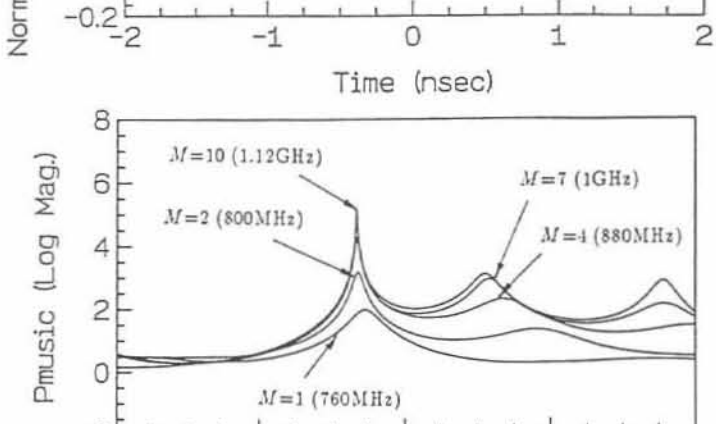

Fig.3. Scattering center estimation of a 101.6mmϕ metal sphere using the MUSIC–SSP. N=20, f_1=5.0GHz, Δf=40MHz. The value in the parenthesis ( ) denotes the required frequency bandwidth.