An Efficient Near Field to Near or Far Field Transformation in Time Domain

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***Abstract*—This paper presents a complementary analysis to the computation scheme previously introduced by Hansen and Yaghijan [1] and [2] for the time-domain near-field to near- or far-field transformation technique. The approach presented here aims to reduce the computation time and memory requirements, which represent the main drawbacks that make difficult the application of the technique to practical cases of interest. Computations with electromagnetic simulation of a circular X-band horn antenna illustrate the accuracy of the proposed method and the rapidity of the resulted near-field to near- or far-field transformation, while using the minimum number of measurement samples.**

Keywords—near-field to far-field transformation, time domain, antenna measurement, sampling theorem

I. Introduction

The Ultra Wide Band (UWB) antennas operating over large bandwidth have attracted a lot of interest over wide telecommunication applications. These polyvalent antennas have to be characterized over the operating frequencies in order to complete the validation of the electromagnetic simulation process results. For these antennas, a time domain analysis appears to be very attractive since using the frequency domain approach, a large number of measurements at different frequencies must be carried out in order to cover the whole working band of the antenna under test (AUT).

In the last decades a quantity of work has been dedicated to the characterization of radiating systems by means of near-field to far field transformation techniques [3]. These techniques are predominantly developed in the frequency domain and are used to characterize the near field and far field or using the near field data to calculate the radiation pattern at a single frequency.

In addition, the near field time domain technique has many advantages over the conventional frequency domain methods. Time domain gating is an efficient way to filter the multiple reflections and presents a promising tool in the measurement accuracy improvement. Also, using time gating, Hansen has shown in [4] that the scan plane truncation error can be removed. Also, using time domain technique, one can characterize non continuous wave radiating structures (non-sinusoidal signals).

However, the main difficulty related to the practical use of time-domain approach concerns the quantity of measured data and measurement time. The required computation time and memory storage can become exorbitant for large measurement surface and large observation time window.

In this paper, an efficient near field to near- or far-field transformation computational scheme is described and discussed. The proposed analysis is based on the exploitation of the minimum number of measurement points, while providing accurate results. We propose to use the reconstruction formulas to rigorously express the near-field between the measurement points and to efficiently calculate the near-field at different distances using a minimal set of time-space measurements. The computation scheme for near-field to near- or far-field transformation we are proposing is described and validated using electromagnetic simulation software (CST Micro Wave Studio)[5].

II. Formulation and Mathematical Analysis

We have developed the near-field to near-field transformation algorithm based on the Green's function representation to calculate the antenna radiation pattern at a different distance x_1 using the data measurement at the distance $x_0<x_1$.

The Matlab routine we have developed uses the direct time domain formula based on the Green's function representation [2]. This direct time formula which expresses the near field to near field transformation is written as

$$\vec{E}(\vec{r},t)=\frac{-1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\vec{R}\times\begin{bmatrix}\frac{1}{cR^2}\vec{x}\times\frac{\partial\vec{E}}{\partial t}(\vec{r_0},t-R/c)\\+\frac{\vec{x}\times\vec{E}(\vec{r_0},t-R/c)}{R^3}\end{bmatrix}dy_0dz_0 \quad (1)$$

The field vector $\vec{E}(\vec{r_0},t)$ is the time domain measured field. The field vector $\partial E(\vec{r_0},t)/\partial t$ is the time derivative of the field at the space position $\vec{r_0}$ and the instant *t*. The measurement plane is expressed by $\vec{r_0}=x_0\vec{x}+y\vec{y}+z\vec{z}$ with $-y_{max}\le y\le y_{max}$ and $-z_{max}\le z\le z_{max}$.

The principle of the near-field to near-field transformation is to calculate $\vec{E}(\vec{r},t)$ for $\vec{r}=x\vec{x}+y\vec{y}+z\vec{z}$ based on the tangential component of $\vec{E}(\vec{r_0},t)$ calculated over a planar surface where $\vec{R}=\vec{r}-\vec{r_0}$ and $R=\left|\vec{r}-\vec{r_0}\right|$. This transformation is consistent for x>x_0.

The near field to far field transformation is a particular case of the near-field to near-field situation. This time *x* goes to infinity and Eq. 1 is expressed as:

$$\vec{E}(\theta,\varphi,t)=\frac{-1}{2\pi c}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\vec{e_r}\times\left[\vec{x}\times\frac{\partial\vec{E}}{\partial t}(\vec{r_0},t+\vec{e_r}.\vec{r_0}/c)\right]dy_0dz_0 \quad (2)$$

with $\vec{e_r}=\vec{R}/R$, and $\vec{E}(\theta,\varphi,t)$ the far-field in the spatial direction (θ,φ).

Using the sampling theorem, (1) and (2) are transformed to the following double summation

$$\vec{E}(\vec{r},t)=\frac{-1}{2\pi}\sum_{m=-Ny}^{Ny}\sum_{n=-Nz}^{Nz}\vec{R}\times\left[\begin{array}{l}\frac{1}{cR^2}\vec{x}\times\frac{\partial\vec{E}}{\partial t}(\overrightarrow{r_{0mn}},t-R/c)\\+\frac{\vec{x}\times\vec{E}(\overrightarrow{r_{0mn}},t-R/c)}{R^3}\end{array}\right]\Delta y_0\Delta z_0 \quad (3)$$

$$\vec{E}(\theta,\varphi,t)=$$
$$\frac{-1}{2\pi c}\sum_{m=-Ny}^{Ny}\sum_{n=-Nz}^{Nz}\vec{e_r}\times\left[\vec{x}\times\frac{\partial\vec{E}}{\partial t}(\overrightarrow{r_{0mn}},t+\vec{e_r}.\overrightarrow{r_{0mn}}/c)\right]\Delta y_0\Delta z_0 \quad (4)$$

where $\overrightarrow{r_{0mn}}=x_0\vec{x}+m\Delta y_0.\vec{y}+n\Delta z_0.\vec{z}$ are the measured field sampling points in the scan plane. The integers N_y and N_z result from the considered scan plane size and sampling criteria. Here we suppose that the scan plane is located outside the reactive zone of the AUT. The measured field can be sampled with a maximum uniform sample spacing defined for band limited functions described by Nyquist-Shannon of approximately $\Delta y_0=\Delta z_0=\lambda_{\min}/2$ with $\lambda_{\min}=c/freq_{\max}$.

In the near-field to far-field transformation formula (2) only the time derivative of the tangential E-field is involved. In Eq. 1 the calculation of the near field involves the tangential E-field components and their time derivative at the measurement distance. Moreover, for near-field to near- or far-field transformation we have to calculate the measured electric field between time samples at the instants $t-R/c$ and $t+\vec{e_r}.\overrightarrow{r_{0mn}}/c$ which requires further interpolation effort. The accuracy of the results depends on the chosen interpolation method.

The time derivative field $\partial E(\vec{r_0},t)/\partial t$ can be determined using a numerical differentiation technique whose accuracy depends on the considered discretization of the measured field (sampling criteria). The measured near field data have to be over-sampled to achieve a consistent result and, as a consequence, the computation time and memory requirement,

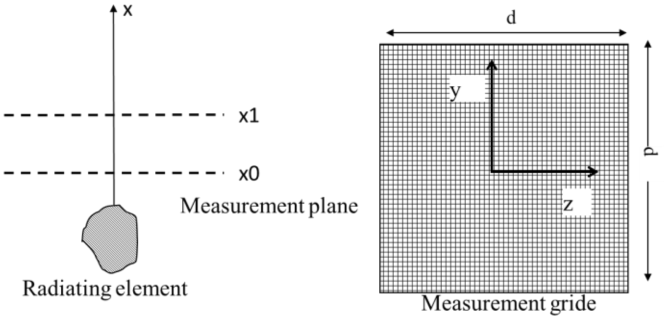

Fig. 1. The radiating element near field measurement at the distance x_0. The tangential components are regularly recorded over a square surface in the zy plane, d=56cm,x_0=12cm, x_1=24cm.

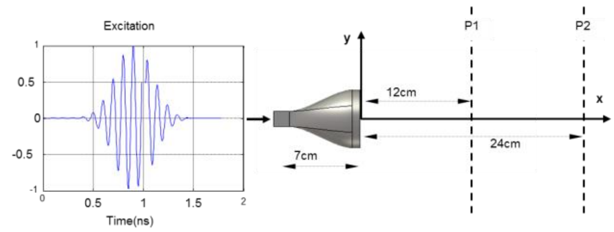

Fig. 2. The circular X-band horn antenna used to generate the near-field data over the planar surface x=12cm (P1). Time-domain waveforms are sampled over a grid depending on the sampling parameters α≥1.

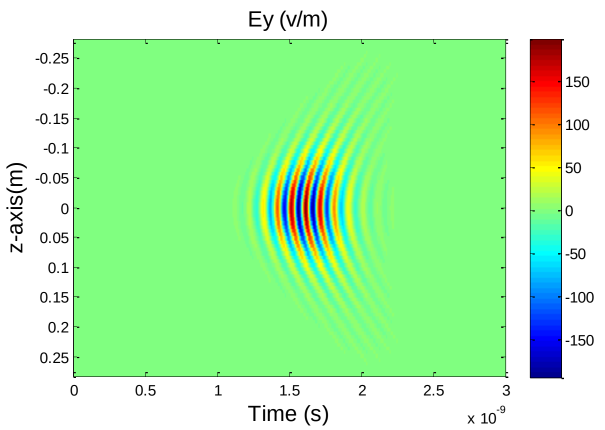

Fig. 3. The Ey (co-polar) component waveform along the z-axis at the measurement distance (x=12cm) for y=0 using the simulation software (Finite Integral Technique)

involving a large number of measured samples in (3) or (4), become prohibitive.

To overcome this difficulty we will exploit the fact that the antenna radiated field is band limited. The key point of the method we propose consists of using of the reconstruction formula for the E-field [4].

For a band limited function $f(t)$ we can write the Fourier transform

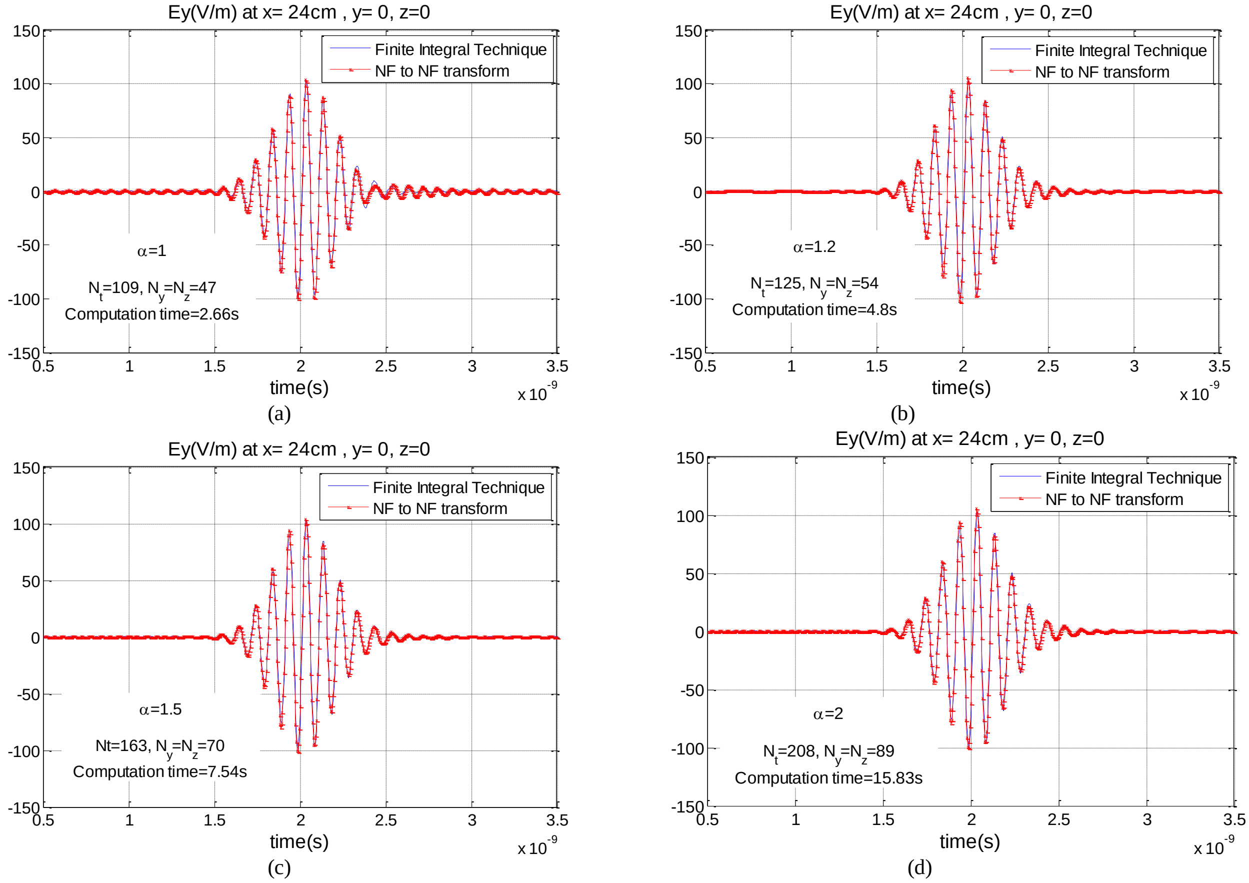

Fig. 4. Time domain near field waveform of the horn antenna at the distance of 24cm from the aperture issued from the simulation software (Finite Integral Technique). Comparison are carried out for different near-field sampling criteria α=1 (a), α=1.2 (b), α=1.5 (c), α=2 (d)

$$f_\omega = \frac{1}{2\pi}\int_{-\infty}^{+\infty} f(t)e^{i\omega t}dt = 0 \quad \text{pour} \quad \omega \geq \omega_{\max} \ . \tag{5}$$

The reconstruction formula allows the time reconstruction of the function $f(t)$ using the minimum number of discrete measurement points $t_0 \leq t \leq t_0 + N_t \Delta t$ respecting the Nyquist-Shannon sampling criterion by

$$f(t) = \sum_{l_t=0}^{N_t-1} \text{sinc}\left[\pi\left(\frac{t-(t_0+l_t\Delta t)}{\Delta t}\right)\right] f(t_0 + l_t\Delta t) \ . \tag{6}$$

The reconstruction formula is used to express the measured field. The E-field is expressed as a function of time as

$$\vec{E}(\overrightarrow{r_{0mn}},t) = \sum_{l=1}^{N_t-1} \frac{\sin\left[\pi\left(\frac{t-t_0}{\Delta t}-l\right)\right]}{\pi\left(\frac{t-t_0}{\Delta t}-l\right)} \vec{E}(\overrightarrow{r_{0mn}},t_0+l\Delta t) , \tag{7}$$
$$= \sum_{l=1}^{N_t-1} h(t).\vec{E}(\overrightarrow{r_{0mn}},t_0+l\Delta t)$$

with

$$h(t) = \sin c\left[\pi\left(\frac{t-t_0}{\Delta t}-l\right)\right], \ t_0 \leq t \leq t_0 + N_t.\Delta t \ . \tag{8}$$

Consequently, the time derivative of the E-field is rigorously written

$$\frac{\partial \vec{E}}{\partial t}(\overrightarrow{r_{0mn}},t) = \sum_{l=1}^{N_t-1} \frac{\partial h(t)}{\partial t}\vec{E}(\overrightarrow{r_{0mn}},t_0+l\Delta t) \tag{9}$$

with,

$$\frac{\partial h}{\partial t}(t) = \frac{1}{t-(t_0-l\Delta t)}\left[\cos\left(\pi\frac{t-t_0}{\Delta t}-l\right)-h(t)\right]. \tag{10}$$

As it can be seen, from (7), (8), (9) and (10) one can determine the E-field and its time derivative rigorously between time-samples provided the sampling Nyquist-Shannon criterion is respected. As a matter of fact, the criteria for time-axis sampling $\Delta t = 1/2\,freq_{max}$ and for spatial-sampling

$\Delta y = \Delta z = c\Delta t$ can be sufficient to accurately calculate the near field to near or far field transformation for antenna characterization.

III. Results

In order to show the viability of the proposed analysis, we consider the time-domain near-field issued from the simulated circular horn antenna. The antenna under test we have used is a circular X-band horn antenna operating at the frequency range of 8-12 GHz. The excitation signal applied to the antenna's port is a Gaussian pulse with a carrier at 10GHz. The time-domain near field data is collected by measuring the time waveform at discrete grid points on a finite scan plane. The Finite Integration Technique simulation software can provide the near E-field at arbitrary positions and times [5]. Thus, we consider the E-field in Ny x Nz points in a fictitious plane as actual near-field signal over the measurement plane $x=x_0$. We are interested at transforming the actual field to determine the field at the distance $x_1>x_0$ using the minimum number of measurement points (Fig. 1). When x_1 goes to infinity the transformation is defined as near-field to far-field transformation. In Fig. 3 we present the antenna near-field issued from the simulation software along the z-axis(x=12cm and y=0).

We consider a parameter α to control the over sampling rate of the near-filed collected over the rectangular grid $-28cm \le y, z \le 28cm$ at $x=12cm=x_0$. The sampling parameter values α=1, 1.2, 1.5, 2 correspond to $\Delta t = 1/(2.\alpha.freq_{\max})$ and $\Delta y_0 = \Delta z_0 = c_0 \Delta t$, where $freq_{\max} = 12GHz$. Respecting each α value we collect over the measurement surface P1 the tangential components of the E-field. Then we calculate the electric field at the planar surface P2 situated at x=24cm using the near-field to near-field transform as shown in Fig. 2. The resulted field is compared to the time-domain near-field over P2 issued directly from the simulation software (Finite Integration technique).

From Fig. 4, we note that the antenna radiated fields over P2 (x=24cm) issued from the simulation software present a good agreement with the fields calculated using the near-field to near-field transformation (from the scan planes P1 to P2) using different sampling parameters (α=1, 1.2, 1.5, and 2). In addition, for α=1, which corresponds to the Nyquist-Shannon criterion, the size of the near field minimum matrix is Ny=Nz=47 and Nt=109. Using α=1, the computation time for each near-field point is 2.66s.

In Fig. 4, we give also the near field matrix size (Nt, Ny and Nz) associated to the sampling parameter α and the corresponding computation time for each calculated near-field point. As it can be seen, considering an over sampled near field data necessitate long calculation duration.

The accuracy of the calculation of the time domain near or far field using over-sampled measured field is not questioned here, nevertheless the efficiency of the field transformation proposed here helps to overcome the main drawback of the near field time domain techniques using the minimum number of measured data.

IV. Conclusion

A complementary analysis to the computation scheme previously introduced by [1][2] for the time-domain near-field to near-field transformation technique has been presented and numerically validated. The approach we have presented aims to optimize the computation time and memory requirements by considering the minimum number of measurement points. The rigorous calculation of the time derivative of the E-field using of the minimum number of near field samples (respecting Nyquist-Shannon criterion) tend to overcome the drawback related to the practical use of time-domain approach. It results that the use of both an optimal representation of the field over the measurement surface and a convenient computation strategy allow the use of a lower number of samples and a faster execution of the near field to near- or far-field transformation in time domain.

References

[1] T. B. Hansen and A. D. Yaghjian "Planar near-field scanning in the time-domain. Part1: Formulation," IEEE Trans. Antennas Propagat. Vol.42, no.9, pp.1280-1291 September 1994.

[2] T. B. Hansen and A. D. Yaghjian "Planar near-field scanning in the time-domain. Part 2: Sampling theorems and computation schemes" IEEE Trans. Antennas Propagat. Vol.42, no.9, pp.1292-1300 September 1994.

[3] A.D. Yaghjian, "An overview of near-field antenna measurements," IEEE Trans. Antennas Propagat., vol. AP-34, pp. 3045, Jan. 1986

[4] . B. Hansen and A. D. Yaghjian "Plane-Wave theory of Time-Domain Fields, near-field scanning applications" IEEE Press, New York (1999)

[5] CST Microwave Studio 2012, www.cst.com.