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Improved Estimation of Impulse Response of Reflector based IRAs using Conjugate Gradient Method

Dhiraj K. Singh[1], D. C. Pande[1], and A. Bhattacharya[2], Member, *IEEE*

[1]Electronics & Radar Development Establishment, Bangalore, India
[2]Indian Institute of Technology, Kharagpur, India

Abstract—**Impulse response of an ultra wide band (UWB) antenna is one of the most important parameters, which in turn helps in deriving other important antenna parameters like gain, antenna factor etc. The excitation input pulse to the antenna is a Gaussian pulse of finite width, hence to get antenna impulse response, far zone electric field data needs to be deconvolve with the input excitation of the antenna. There are no pure closed form deconvolution methods that are widely accepted and numerically stable. Reflector based half impulse radiating antenna (HIRA) is analyzed using finite difference time domain (FDTD) method. Estimation of impulse response is done on both the analysis and measured input output data using both time domain as well as frequency domain methods. This paper focuses on the improvement of the timing characteristics of impulse response like late time ringing and group delay. Time domain technique like conjugate gradient method shows clear advantage over the Fourier transform method, especially for measured data. The estimated impulse response using conjugate gradient method removes imperfections of input signal and the late time ringing is reduced to significantly low level.**

***Index Terms*— Deconvolution, Conjugate Gradient, ACD, FDTD, HIRA, UWB**

1. INTRODUCTION

Impulse response of an ultra wideband (UWB) antenna is one of the most important parameters and is used to derive most of the frequency domain parameters of the antenna. The error incurred in the estimation of impulse response may percolate to the other derived antenna parameters. The calculation of impulse response of a system from its output and input data is an inverse problem [1-5] and there may not be a unique solution. The artifacts introduced in the impulse response due to numerical error may lead to ringing in the estimated impulse response, which may mask returns from nearby target for short range radar applications, like through wall imaging radars, etc. Hence correct estimation of the antenna impulse response is vital .The estimation of the impulse response can be done either in time domain or in frequency domain. Conjugate gradient method and Fourier transform method used as time domain and frequency domain technique respectively. Simulated and measured data of the reflector-based half impulse radiating antenna (HIRA) [10-11] is used for the estimation of its impulse response. This paper focuses on the improvement of timing characteristics of impulse response like late time ringing, group delay, and removal of source imperfections. Some of the important parameters of UWB antennas are discussed in section-2, frequency domain and time domain deconvolution algorithms are elaborated in section-3, estimated impulse response using Fourier method and conjugate gradient method both for simulated and measured data is presented in section-4, conclusion is presented in section-5.

2. ANTENNA CHARACTERISTICS

UWB antenna needs to be evaluated for its time domain characteristics apart from conventional parameters. Time domain antenna test ranges are becoming popular in recent past [6-7], especially for UWB and impulse antennas because its low cost, less time consuming and there is no requirement of anechoic chambers. Apart from the standard antenna parameters like antenna gain, beam width etc followings other important parameters to characterize UWB antennas completely for both time and frequency domain performance:

1. Antenna Impulse Response: Antenna impulse response is ideally defined by the response of the antenna for Dirac delta input excitation but practically the input excitation signal will have finite width, hence there may be requirement to deconvolve output and input signals to get the antenna impulse response. The time domain transmit and receive relation of two antenna system[6-8] placed in far field in free space is given below:

$$\frac{E_{rad}(t)}{\sqrt{377\Omega}} = \frac{1}{2\pi rc} h_N(t) \circ \frac{dV_s(t)/dt}{\sqrt{Z_{in}}} \tag{1}$$

$$\frac{V_r(t)}{\sqrt{Z_{in}}} = h_N(t) \circ \frac{E_{inc}(t)}{\sqrt{377\Omega}} \tag{2}$$

Where $E_{rad}(t)$ is radiated electric field, r distance away from the antenna ,c speed of light ,$V_s(t)$ is excitation voltage, $E_{inc}(t)$ is incident electric field , $V_r(t)$ is received voltage, $\circ$ is convolution operator and $h_N(t)$ is normalized impulse response of the antenna having unit in meter per second. The above relation is given for dominant polarization in bore sight direction of the antenna. The above relation can be combined for two antenna system in terms of excitation and received voltage.

$$V_r(t) = \frac{1}{2\pi rc} h_{N,Rx}(t) \circ h_{N,Tx}(t) \circ \frac{dV_s(t)}{dt} \tag{3}$$

The normalized frequency domain impulse response of the antenna in a two similar antenna system is given by:

$$\vec{h}_N(\omega) = \sqrt{\frac{2\pi rc\overrightarrow{V_r}(\omega)}{j\omega\overrightarrow{V_s}(\omega)}} \tag{4}$$

Antenna impulse response can be calculated using equation (1-3) by time domain deconvolution techniques or using equation (4) by frequency domain (FD) methods.

The first issue involved in deconvolution problem is the division by complex number with small magnitude. This can be solved by identifying $H(f)$ as raw ratio and then applying a "limiting ratio" to the raw ratio, so that $|H(f)|$ will be limited to $H_{\min}$, where

$$H_{\lim}(f) = \frac{H(f)}{|H(f)|}\sqrt{H_{\min}^2 + |H(f)|^2} \tag{5}$$

$$H_{\min}(f) = \max|H(f)| \times q \tag{6}$$

Where q is the limit ratio, typical value of q is set to 0.01 for all the data sets used in subsequent section. The effect of this procedure is that the magnitude of the raw ratio is adjusted to be so smaller than q times the maximum of the raw ratio, while preserving the phase. The next step in deconvolution is applying low pass filter to the limited ratio. The filter normally used are true Butterworth or simplified Butterworth as described by

$$G(f) = \frac{1}{1 + \left(\frac{f}{f_0}\right)^{2N}} \tag{7}$$

Where f_0 is cut off frequency of the filter and N is order of filter.

2. Ringing: The ringing τ_r of an IRA is undesired and usually caused by resonances due to energy storage or multiple reflections in the antenna. It results in oscillations of the radiated pulse after the main peak. The duration of the ringing is defined as the time until the envelope has fallen from peak value below a certain lower bound.

3. Group Delay: The group delay of an antenna characterizes the frequency dependence of the time delay. It is defined in frequency domain

$$\tau_g(\omega) = -\frac{d\varphi(\omega)}{d\omega} = -\frac{d\varphi(\omega)}{2\pi df} \tag{8}$$

Where $d\varphi(\omega)$ is frequency dependent phase of the signal

The mean group delay is a single number for the whole UWB frequency range.

$$\overline{\tau_g} = \frac{1}{\omega_2 - \omega_1}\int_{\omega_1}^{\omega_2} \tau_g(\omega)d\omega \tag{9}$$

A nondistorted structure is characterized by a constant group delay, i.e., linear phase, in a relevant frequency range. The non linearities of a group delay indicate the resonant character of the device, which implicates the ability of the structure to store energy. It results in ringing and oscillations of the antenna impulse response. A measure of constancy of the group delay is the deviation from the mean group delay $\tau_{g,r}(\omega)$.

$$\tau_{g,r}(\omega) = \tau_g(\omega) - \overline{\tau_g} \qquad (10)$$

The conventional Impulse Radiating Antennas had been designed for 200 Ω input impedance wherein the conical plate transmission line feed used is of 400 Ω characteristic impedance. The input impedance of this antenna is reduced to 100 Ω by using half reflector, ground plane and two feed arms known as half impulse radiating antenna[9] (HIRA) shown in Fig. 1.The conventional HIRA as shown in Fig.1. needs an 50Ω to 100Ω impedance adaptor[9] for connecting it with standard 50Ω waveform generators.

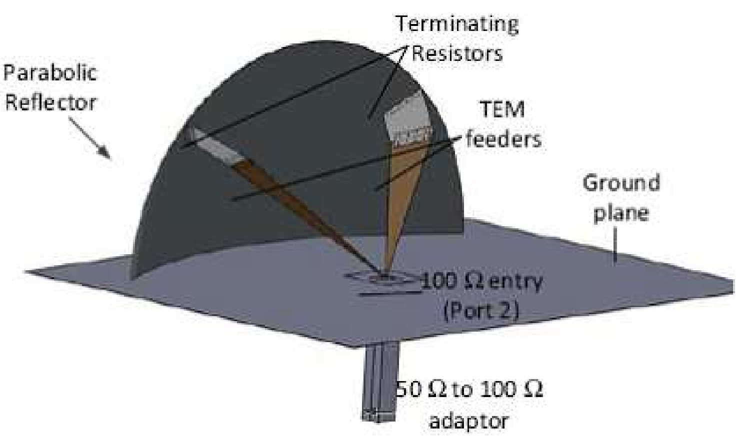

Fig. 1.Schematic of Conventional HIRA

ACD fed HIRA is designed for 50Ω input impedance so that it can be readly connected with 50Ω standard instrumentations. The full ACD fed IRA was analyzed in [10-11] and its half reflector version was realized to reduce the input impedance of the antenna to nearly 50Ω .Here ACD fed HIRA as shown in Fig.2 is analyzed in time domain using finite difference time domain solver XFDTD (v7.1). The excitation waveform used for simulation of the antenna was a Gaussian pulse of 50ps width as shown in Fig.3.The calculated far-zone electric field in the bore sight direction of the antenna is shown in Fig.11.The far zone electric field as shown in Fig.4. consists of a prepulse of duration ~ 1.23ns (2F/c), and an impulse signal that is first time derivative of the excitation signal.

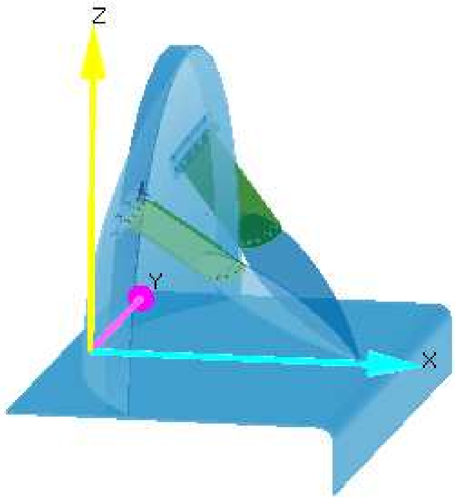

Fig. 2. Solid model of new HIRA

3. DECONVOLUTION PROBLEM

The calculation of impulse response of a system from its output and input data is an inverse problem and there may be more than one solution. The deconvolution problem can be simplified to division problem by using Fourier transform method as shown below:

$$y(t) = x(t) * h(t) \tag{11}$$

Where, * operator implies convolution

Taking the Fourier Transform of the equation(11) we get: $Y(j\omega) = X(j\omega)H(j\omega)$

$$H(j\omega) = Y(j\omega)/X(j\omega) \tag{12}$$

In practical measurements, the exact knowledge of the time signals is not possible. As a result of bandwidth limitation of the time signal detector and the digitization and acquisition processes, the acquired waveform differs to a certain extent from the true signal [4-5]. Denoting the acquired waveforms by

$$x_w(t) = x(t) + x_e(t) \tag{13}$$

and

$$y_w(t) = y(t) + y_e(t) \tag{14}$$

Where, $x_e(t)$ and $y_e(t)$ represent the error components respectively.

And the corresponding frequency domain form is $[Y_w(j\omega) - Y_e(j\omega)] = H(j\omega).[X_w(j\omega) - X_e(j\omega)]$ (15)

Consequently, $H(j\omega)$ is given by,

$$H(j\omega) = \frac{Y_w(j\omega)}{X_w(j\omega)} \tag{16}$$

In practical solutions *x(t)* is a band-limited signal, i.e., $X(j\omega)$ has a finite bandwidth and , consequently, there exists a region of frequencies approximation, $X(j\omega) \approx X_w(j\omega)$ is not a good one. The deconvolution $H_e(j\omega)$ will contain some fairly high values. These values can be viewed as a sequence of spikes. Upon the application of inverse Fourier transformation to $H_w(j\omega)$, the spikes that were concentrated in the frequency regions of small $X(j\omega)$ produce error contributions that are spread over the entire time-domain epoch and if the error components are high, they may dominate the time-domain transformation, thereby hiding most of the details of $h_w(t)$.

Fourier transform method has following limitations:

1. The above method leads us to the correct result only in the ideal case, i.e., when there is no noise in the input and the output. Practically, this never is the case. At certain ω, the values of $X(j\omega)$ might be (erroneously) very small. $Y(j\omega)$, when divided by such a small quantity (and when $Y(j\omega)$ is not of the same order as $X(j\omega)$, we get extremely large values for $H(j\omega)$, causing the error in the result.
2. In some cases the $h(t)$ may have a dc step which is incapable of being recovered in the frequency domain method. This can only be recovered following the time domain technique.

3. Aliasing is one of the major problems faced while using deconvolution in the frequency domain. This is because the transient response is time limited hence they are not band limited. However, it is possible to avoid the problem of aliasing by operating wholly in the time domain.

CONJUGATE GRADIENT METHOD:

The conjugate gradient (CG) algorithm [1-3] is an iterative search procedure which calculates a set of approximate solutions $\{a_k\}$ obtained by searching along a set of direction vectors $\{p_k\}$**.** Efficiency of the search procedure results from reduction in the dimensionality of the error subspace. The error vector may be shown to be X-orthogonal to all previous search directions, on any given iteration. Thus, the minimum is achieved (to within available arithmetic precision) in at most N iterations. The CG algorithm followed is as given below.

Let $\boldsymbol{h_0}$ be the initial "guessed" impulse response, **X** be the input and **Y** be the output.

1. After starting with the initial guess, $\boldsymbol{h_0}$, convolve it with $\boldsymbol{X}$ and obtain $\boldsymbol{Q}$ such that $Q = X * ho$
2. Next find the initial residue $\boldsymbol{R_0}$ as the difference of $\boldsymbol{Q}$ and $\boldsymbol{Y}$ ($(= \boldsymbol{Q} - \boldsymbol{Y})$
3. Find the correlation (or matrix multiplication) of $\boldsymbol{X}$ and $\boldsymbol{R_0}$ to obtain $\boldsymbol{S}$.
4. Next obtain $\boldsymbol{P_0}$ as $-\boldsymbol{b_0 S}$, where $\boldsymbol{b_0} = |\boldsymbol{S}|^{-2}$ (|S| is the absolute value or magnitude of S).
5. Obtain $\boldsymbol{\alpha_0} = ||\boldsymbol{X} * \boldsymbol{P_0}||^{-2}$ where * is the convolution operation and the || || operator implies norm.

The above equations create the initial set of conditions required to start the iterative process. The set of iterative operations is described below:

a. The residue $\boldsymbol{R_{k+1}} = \boldsymbol{R_k} + \boldsymbol{\alpha_k}\,(\boldsymbol{X} * \boldsymbol{P_k})$ is computed and checked for the following condition:

$$|R_k(t)| \geq C\,\{\int_0^T |h(t)|\,d\tau + 1\}$$

Where, $\alpha_k = ||X * P_k||^{-2}$

C is number of bits used in the quantization process

T is the duration of the signal

The above inequality checks for the residue (error) being more than a certain tolerance value.

b. $P_{k+1} = P_k - b_{k+1} S_{k+1}$

Where, S_{k+1} = correlation of $\boldsymbol{X}$ and $\boldsymbol{R}_{k+1}$ (or simple matrix multiplication)

and $bk_{+1} = ||\boldsymbol{S}_{k+}||^{-2}$

c. Compute $\boldsymbol{h}_{k+1} = \boldsymbol{h}_k + \boldsymbol{\alpha}_k \boldsymbol{P}_k$

The above set of equations runs iteratively until the residue (error) falls below the specified tolerance value. This iterative loop needs to run at most n number of times where n is the dimension or length of the input (output) samples containing vector.

4. RESULT AND DISCUSSION

Fourier transform and conjugate gradient algorithms are applied on the simulated as well as measured time domain data obtained for ACD fed HIRA. The excitation signal used as input for ACD fed HIRA is shown in Fig.3 and the far zone electric field calculated at equivalent far field distance of 1m is shown in Fig.4.The transmitting relation of the antenna is used for estimation impulse response wherein excitation signal shown Fig.3 is $V_s(t)$ and the calculated far zone electric field for different antenna configurations is $E_{rad}(t)$. The impulse response estimated using Fourier transform method followed by simplified Butterworth filter of order 5 and cutoff frequency 15GHz is shown in Fig.5.The relative group delay calculated from this impulse response data is plotted in Fig.6.The impulse response estimation is done based on the simulated data wherein no measurement noise involved still there is late time ringing observed in the response primarily because of non-optimum setting of threshold value in the implementation of low pass filter. Time domain iterative technique like conjugate gradient method used on the same set of simulated data and the estimated impulse response and the calculated relative group delay is shown in Fig.7 and Fig.8 respectively. The data samples for each simulated result are around 2000 and the sampling interval is 3.86ps. The estimated impulse response using CG method is much cleaner and ringing is substantially reduced and the relative group delay is much flatter in the entire frequency range.

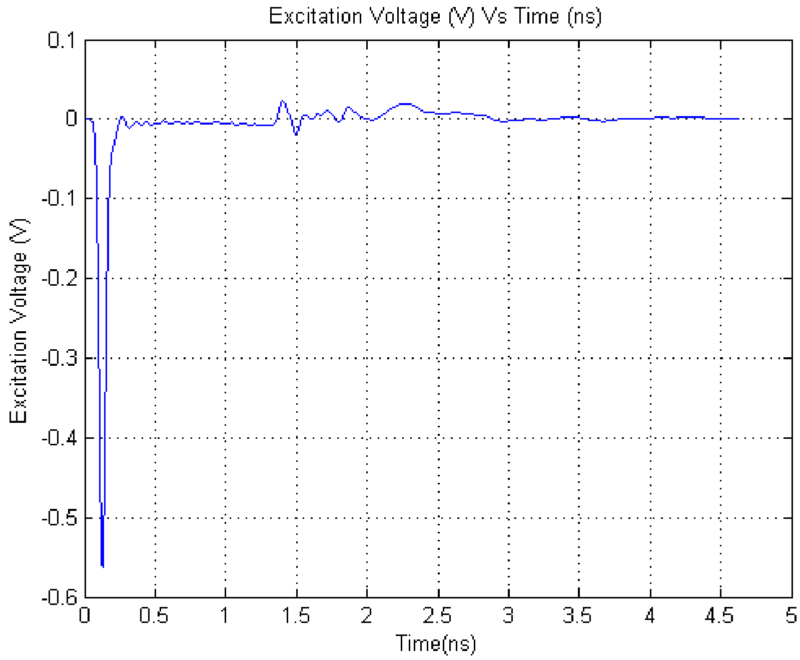

Fig. 3.Input excitation signal (Simulation)

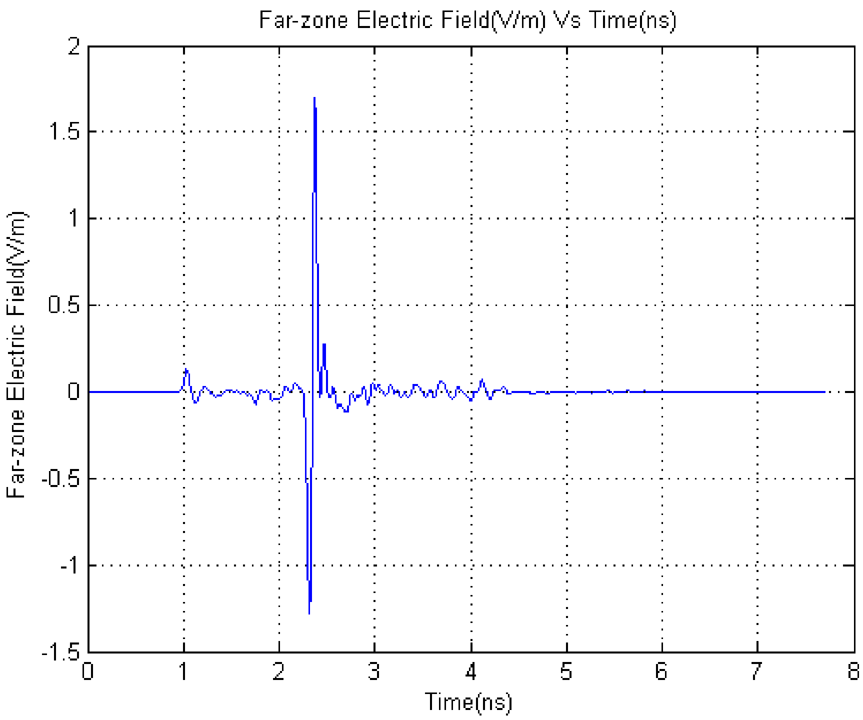

Fig. 4.Far zone electric field (Simulation)

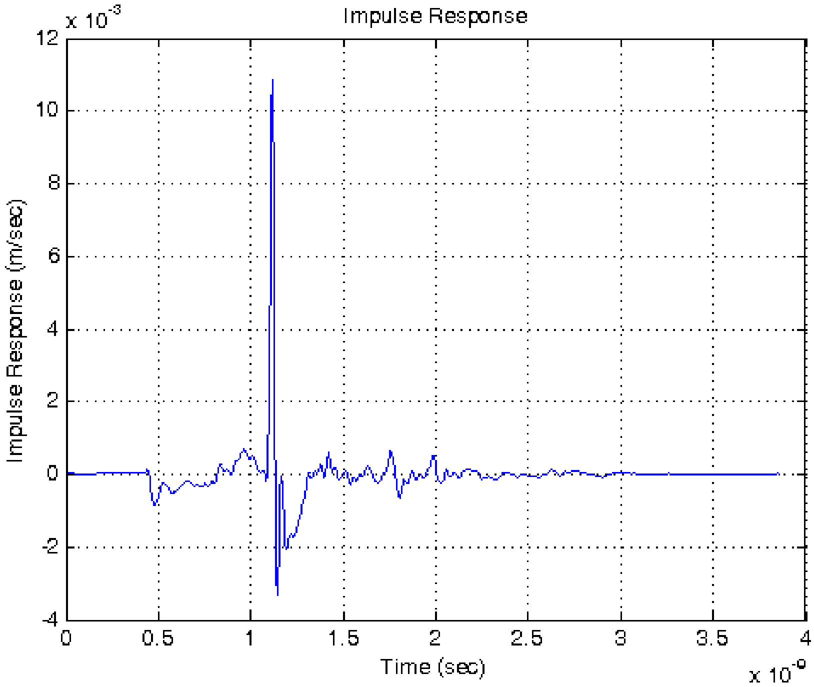

Fig. 5.Estimated impulse response using Fourier transform method

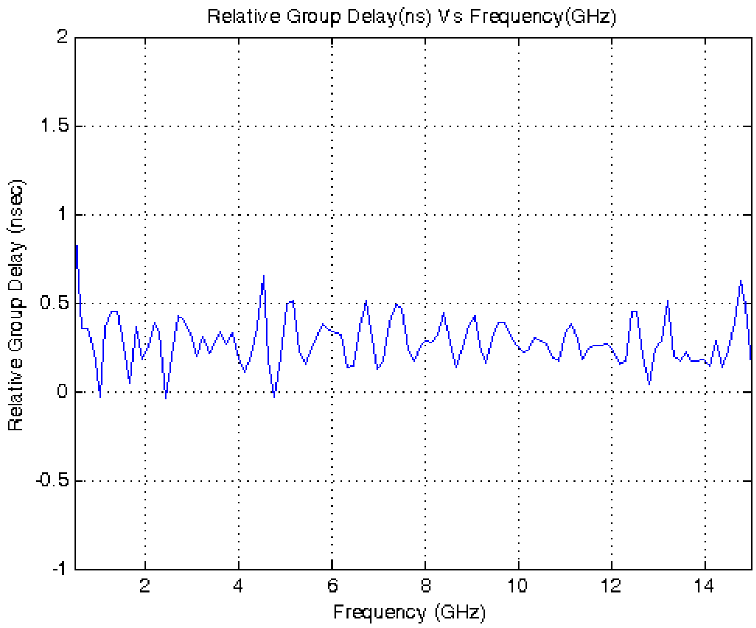

Fig. 6.Relative Group delay using Fourier transform method

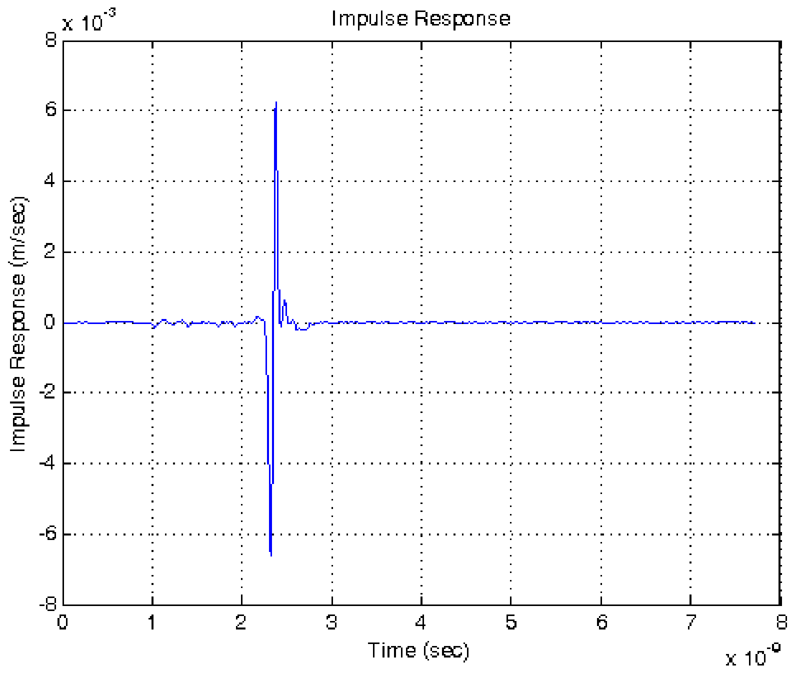

Fig.7. Estimated impulse response using Conjugate Gradient method

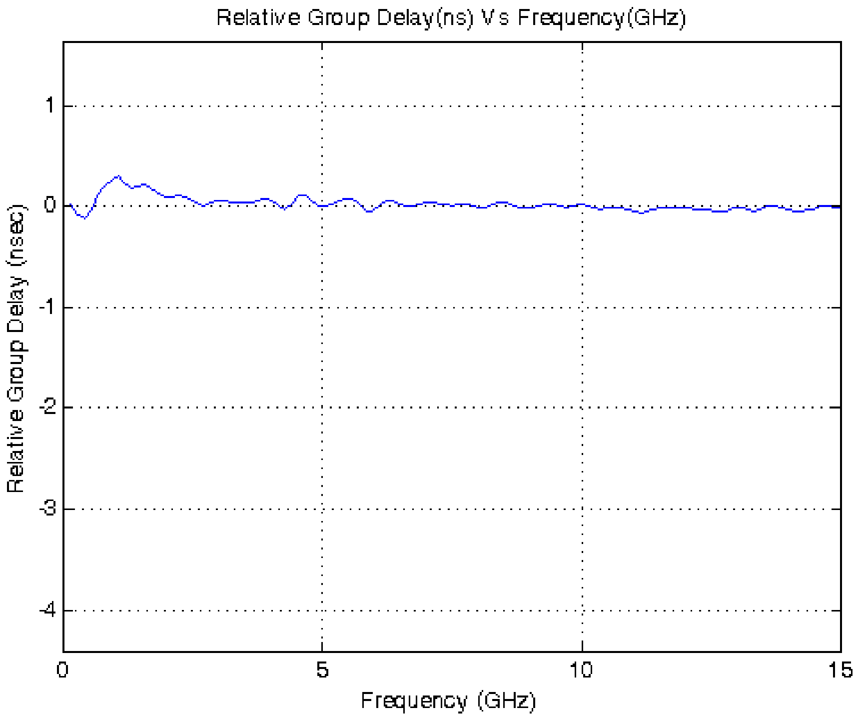

Fig. 8.Relative Group delay using Conjugate Gradient method

The effective gain of the novel HIRA is derived using equation (17) [6] from the estimated impulse response from Fourier transform method and conjugate gradient method.

$$G_{eff}(\omega) = \frac{4\pi f^2}{c^2}\left|\vec{H}(\omega)\right|^2 \tag{17}$$

The effective gain of the novel HIRA in the bore sight direction obtained from the FDTD solver (XFDTD), Fourier transform method and conjugate transform method is plotted against frequency as shown in Fig.9.The plot shows that gain obtained from FD and CG method closely matches with the XFDTD result for most of the frequency range.

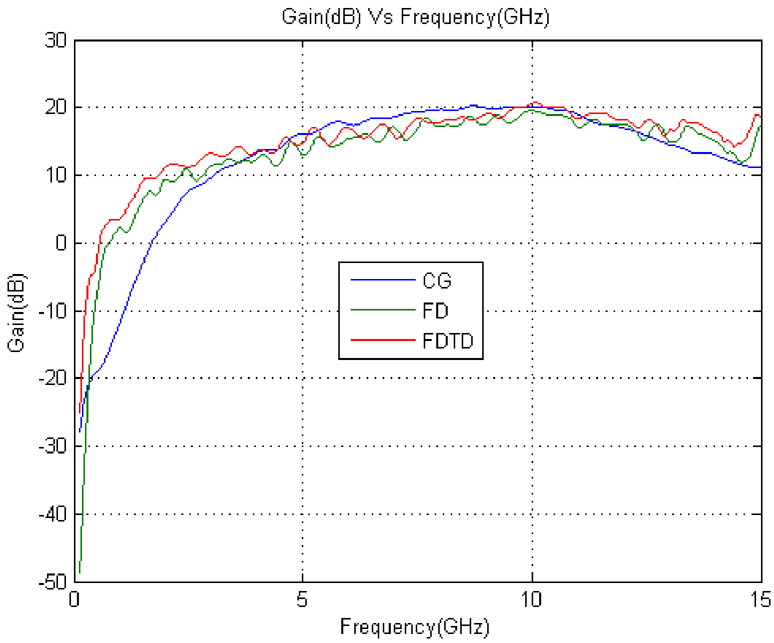

Fig. 9. Gain (dB) Vs Frequency (GHz)

To prove the numerical stability and robustness of the Fourier transform and CG algorithm, input excitation and far zone electric field data of four different designs of IRAs discussed in [11] used to estimate their respective impulse response. The estimated impulse response of all the four different IRAs using Fourier transform and CG method is shown in Fig.10 and Fig.11 respectively. Conjugate gradient algorithm consistently converged for all the data sets with an initial guess value for $\boldsymbol{h_0=0}$. Its shows that CG method gives much cleaner impulse response compared to Fourier transform method.

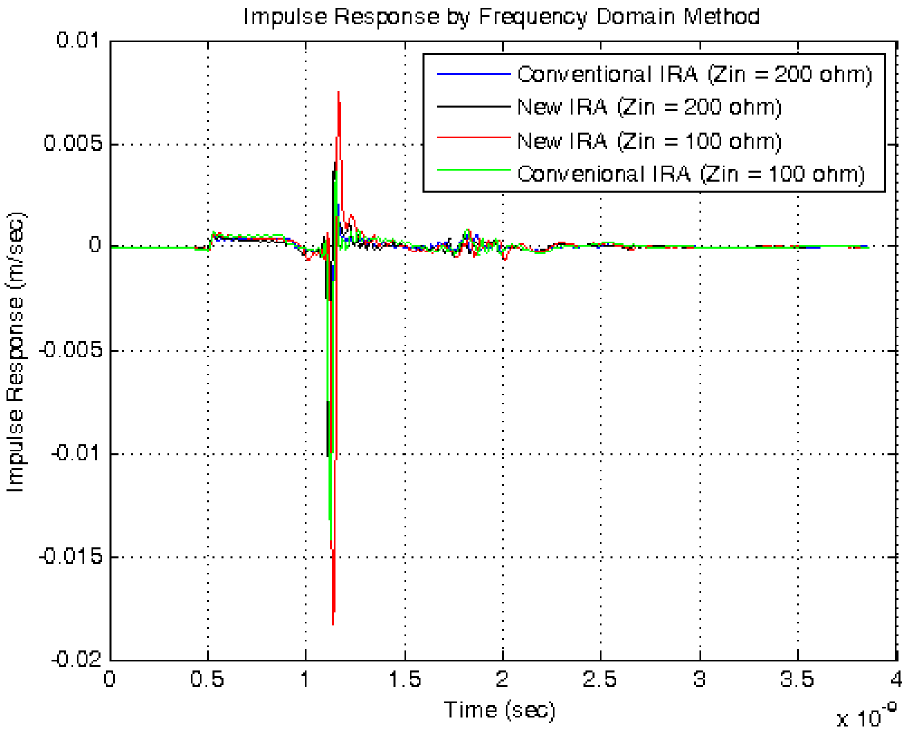

Fig. 10. Impulse response of full IRAs using Fourier transforms method

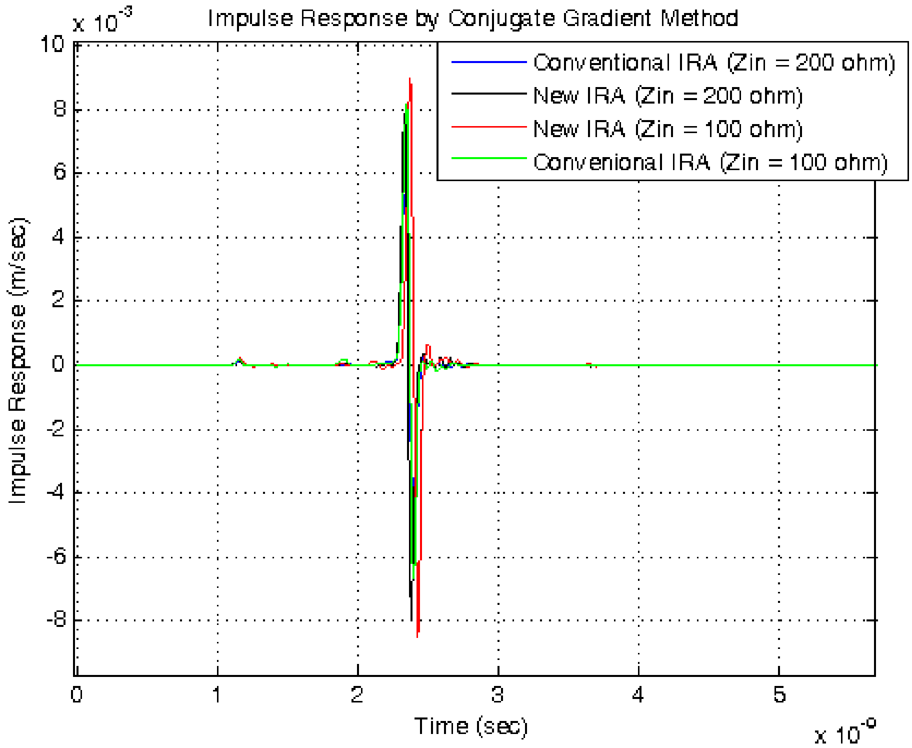

Fig. 11. Impulse response of full IRAs using Conjugate gradient method

The simulated data obtained does not contain any measurement error and external noise. The real test of the deconvolution algorithm lies in evaluating its performance on the measured data which may contain cable pickups, external noise, measurement error etc. The realized ACD fed HIRA is shown in Fig.12 was excited using UWB arbitrary wave generator (AWG) (Tektronix AWG 7122C) and the electric field was measured using ACD sensor (prodyn AD-70D) on an Oscilloscope (Tektronix TDS71604 DPO 16 GHz). The input excitation pulse used for antenna evaluation is a gaussian derivative pulse as shown in Fig. 13. The measured time domain response of the new HIRA is first time derivative of the input excitation pulse as shown in Fig. 14.The measured response in Fig.14 shows lot of ringing after the main pulse may be due cable pickup, external noise, measurement error etc. This may lead to the masking of response of a low RCS targets in short range radar applications. The measured data from the sensor as shown in Fig.14 is used without corrections, as required to get electric field data from sensor output, in CG algorithm to get the estimated impulse response as shown in Fig.15.The estimated impulse obtained from the measured data shows much cleaner response and the late time artifacts are completely removed.

Fig. 12 Realized New HIRA

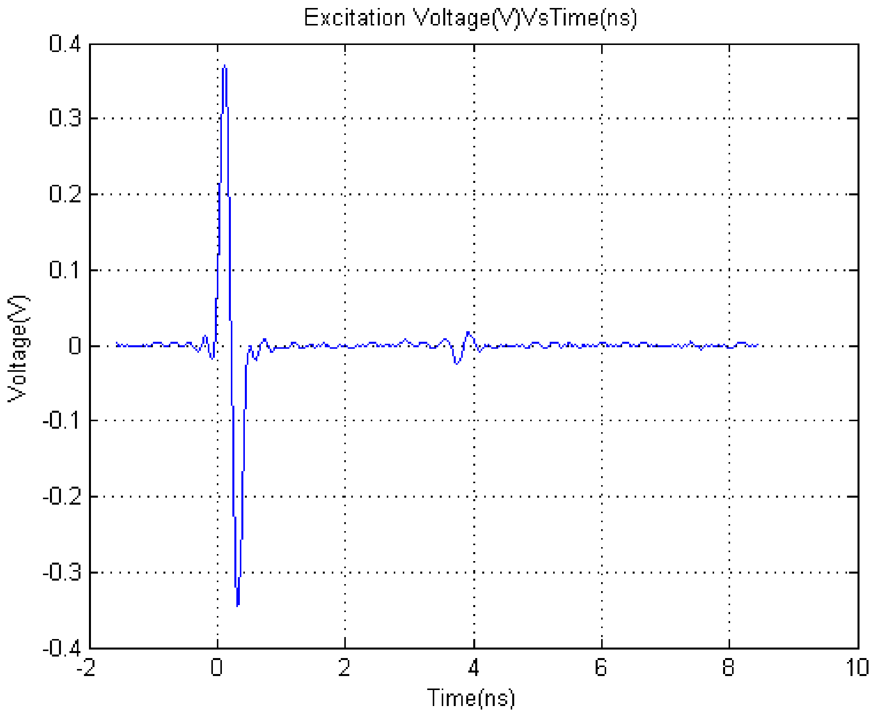

Fig. 13 Excitation signal used for time domain measurement

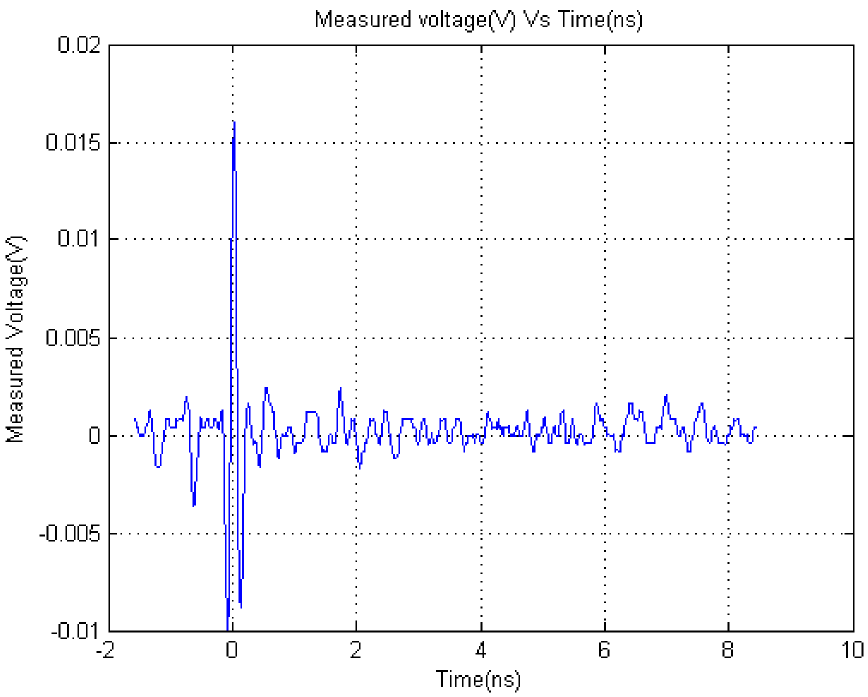

Fig. 14 Measured time domain response of new HIRA

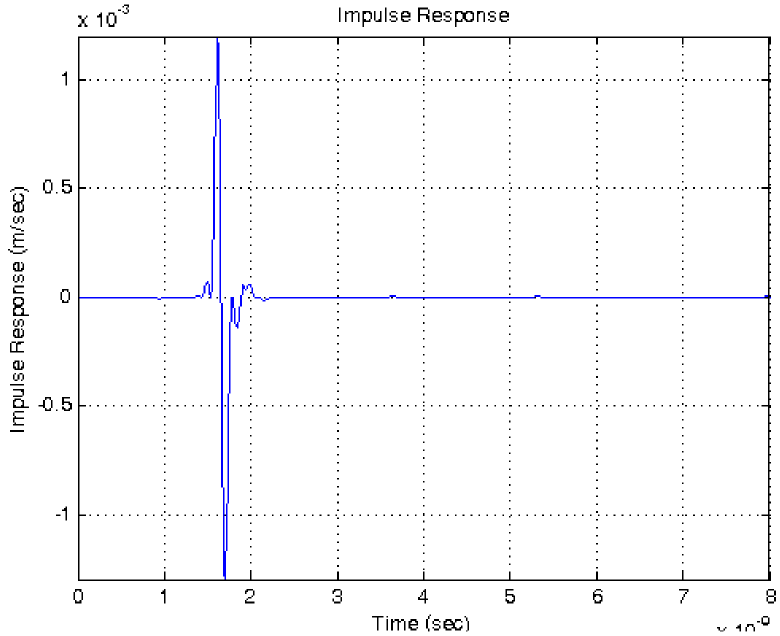

Fig. 15. Impulse response of ACD fed HIRA using Conjugate gradient method

5. CONCLUSION

Impulse response of an antenna carries lot of information about its characteristics. Estimation of impulse response from output and input data is one of the most important steps in finding other important time domain as well as frequency domain antenna parameters. Deconvolution techniques like conjugate gradient and Fourier transform method applied on simulated data for ACD fed HIRA and four other full IRAs. Conjugate gradient method shows much cleaner response for all the simulated data compared to Fourier transform method. The estimated impulse response using CG method shows that it removed all the artifacts like imperfection in excitation signal, cable pickup, external noise and measurement error. Time domain technique like CG method is much robust and stable for estimation of impulse response UWB antennas particularly for IRAs.

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