4B1-5

Late time response signature analysis in UWB sensors

#M.Gashinova, M. Cherniakov, L. Daniel
Microwave Integrated System Lab., EECE Department, School of Engineering,
The University of Birmingham,
Birmingham, B15 2TT, UK, m.s.gashinova@bham.ac.uk

1. Introduction

The limitations of existing systems for concealed, body-worn weapons & explosives (CW&E) detection at a stand-off distance have been discussed in [1]. In this paper the latest research results in the development of 'early warning' system for CW&E detection based on the Late Time Response (LTR) signature analysis in UWB radar will be presented.

Efficiency of signature extraction and its correct interpretation depend on system subcomponents characteristics (antennas first of all) as well as processing algorithms. The algorithm validation in the research is made by using full-wave modeling of the output waveform and its comparison with analytical solution. The time response measurements incorporated with antennas calibration are implemented. At the test stage a Vector Network Analyser (VNA) was used as a signal source. Measurements were set in the anechoic chamber to provide a complete signal control and initial comparison with outdoors measurements is made. The signal processing is based on equalization and spurious component removing and eventually a generalized Matrix Pencil-of-Function (MPoF) approach [2] is applied to retrieve the parameters of LTR. Finally, the preliminary results of analysis of LTR part of reflected signal for three configurations of canonical targets will be presented.

2. LTR representation and method of the analysis

A radar target can be represented by an s-plane transfer function (Singularity Expansion Method [3]) having both poles and zeros. The unique signature of the target is defined by those poles and residues extracted from the LTR of the transient signal. The LTR has the form of a sum of damped sinusoids [3,4]:

$$h(t)=\sum_{1}^{N} R_n e^{\sigma_n t}\cos(\omega_n t+\phi_n) \quad \text{for } t>T_L \quad \text{and} \quad H(s)=\sum_{n=1}^{N}\frac{R_n}{2}e^{j\phi_n}\frac{1}{s-s_n}+\sum_{n=1}^{N}\frac{R_n}{2}e^{-j\phi_n}\frac{1}{s-s_n^*} \tag{1}$$

where T_L is the start of the late-time part of the backscattered signal, R_n and φ_n are the aspect-dependent amplitude and phase of the mode, ω_n and σ_n are aspect-independent frequency and damping coefficients correspondingly; $s_n=\sigma_n+i\omega_n$ is a Laplace variable. Thus, N pairs of complex frequencies and their complex conjugates are the poles of the transfer function $H(s)$. Generally we need to represent the sampled version of empirical signal $h(t_k)$ by the sum of damped sinusoid and additive Gaussian noise:

$$h(t_p)=\sum_{k=1}^{3}\left(a_k e^{f_k t_p}+a_k^* e^{f_k^* t_p}\right)+\sigma^2\mathrm{randn}(t_p) \tag{2}$$

where $\{a_k, f_k\}$ is a set of complex conjugated generalized amplitudes and frequencies with $\varphi_k=\arctan(\mathrm{Im}(a_k)/\mathrm{Re}(a_k))$ and $R_k=\sqrt{\mathrm{Re}^2(a_k)+\mathrm{Im}^2(a_k)}$, $\omega_k=\mathrm{Im}(f_k)$ and $\sigma_k=\mathrm{Re}(f_k)$. In order to extract these poles and residues the generalized MPoF method [2] is used for sampled late-time signal $h(t_p)$. An improved algorithm has been developed where the truncation of matrices of information signals and poles selection during Singular Value Decomposition (SVD) are built in such a way that allows essential increase in the accuracy of the approach. The algorithm justification and validation of the approach have been done by analysis of an artificially synthesized signal combined with damped sinusoids and by analysis of the processed experimental data as well as full-wave simulated signal. In order to implement first procedure and to illustrate noise sensitivity, we applied developed software to synthesized signals at the additive Gaussian noise background [1]. It was shown that the highest error of extracted frequency/residue pairs corresponds to a sinusoid with the largest damping coefficient. At the next step the full-wave CST EM Studio modeling of the transient response

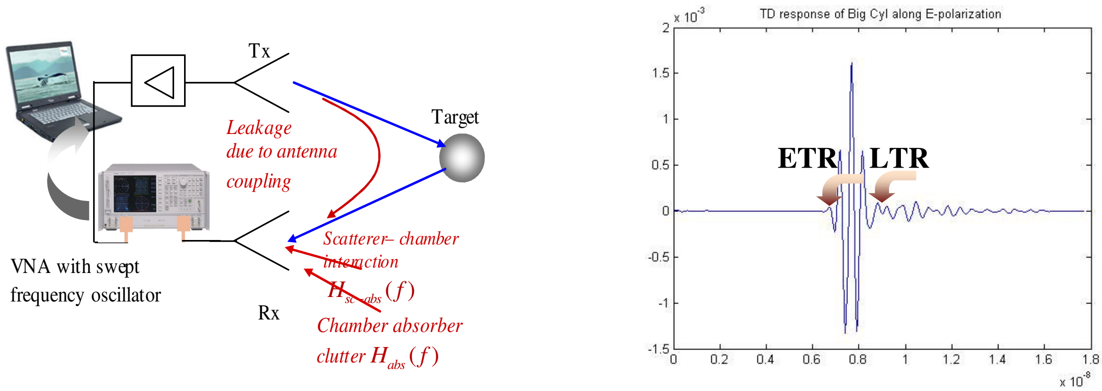
ISBN: 978-4-88552-223-9 C3055©IEICE

and comparison with theoretically predicted data for a sphere and cylinder were done. Scattering on the cylinder enables the extra information on target shape for the different polarizations of the plane wave because of different sets of the excited mode parameters.

Procedure of the signal reconstruction after MPoF processing of simulated output and by theoretical parameters is based directly on (2). It could be concluded [5] that only the lowest resonant modes have essential amplitudes to carry energy high enough to be distinguished in the presence of noise. Agreement between theoretically predicted frequencies and those extracted from the LTR confirms made assumptions. Finally, the parameters were extracted for the cylinder irradiated by incident waves polarized along and across it's axis. Calculated frequencies also agree with theoretical ones and demonstrate above suggestions about the excitation of different modes for the different aspect angles.

3. FD Measurement and Processing Data

Test laboratory environmental setup in anechoic chamber is shown in Fig. 2 a). Holder for antennas is constructed to allow rotation. TD waveform of the response is demonstrated in Fig. 2. b).



a) b)

Fig. 2. . a) Scheme of measurement of backscattered signal in FD. b) Measured in FD and processed in TD response of sphere.

Below the processing procedure of signal measured in the frequency domain is presented. VNA drives the transmitting antenna and collects the signal from the receiving antenna. In order to refine the object backscattered signal the leakage field and the chamber absorber clutter field must be eliminated. In this way three FD response measurements were made.

Face-to-Face antenna transfer function measurement: $S_{FF}(f) = S(f)H_{ar}(f)H_C(f)H_{at}(f)$ (3)

where $S(f)$ is the transmitting signal in FD, $H_{ar}(f)/H_{at}(f)$ is a transfer function of receiving /transmitting antenna.

Side-by-Side background measurement – to remove leakage between two adjacent antennas

$$S_{SS}(f) = S(f)H_{ar}(f)(H_L(f) + H_C(f))H_{at}(f) \quad (4)$$

where $H_L(f)$ is antenna coupling (leakage) transfer function and $H_C(f)$ is the transfer function of the chamber absorber clutter.

Target measurement: $S_T(f) = S(f)H_{ar}(f)(H_L(f) + H_C(f) + H_{TC}(f) + H_T(f))H_{at}(f)$ (5)

where $H_{TC}(f)$ is transfer function of the multipath interaction between target and chamber, $H_T(f)$ is the transfer function of the target which scatters the transmitted field.

To eliminate the leakage and chamber clutter which are common for Side-by-Side and target measurements the leakage signal (4) is subtracted from the target scattering signal (5):

$$S_T(f) - S_{SS}(f) = S(f)H_{ar}(f)(H_{TC}(f) + H_T(f))H_{at}(f) \quad (6)$$

Assuming that i) the transfer function of the signal from VNA (as a generator) has rectangular shape, i.e $S(f) = \mathbf{1}(f)$, ii) transmitting and receiving antennas transfer functions are equal, i.e. $H_{ar}(f) = H_{at}(f) \equiv H_a(f)$ and iii) $H_C(f) \equiv 1(f)$, (3) and (7) reduce to

$$S_{FF}(f) = H_a(f)H_a(f) \quad (7)$$

$$S_T(f) - S_{SS}(f) = H_a(f)(H_{TC}(f) + H_T(f))H_a(f) \quad (8)$$

In (8) the antenna responses $H_a(f)$ affect the overall signal. Once the antennas frequency response

$S_{FF}(f)$ is known a signal can be obtained, this makes the antennas frequency response flat at the constant level 1. Equalizing signal I must be equal to $1/S_{FF}(f)$. If the inverse signal is applied in (8) then:

$$S \rightleftarrows (S_T(f) - S_{SS}(f)) \cdot I = H_a(f)(H_{TC}(f) + H_T(f))H_a(f) \cdot I \overset{H_{TC}(f)\approx 0}{=} 1(\mathrm{f}) \cdot H_T(f) \tag{1.9}$$

$$IFFT\left[((S_T(f) \text{-} S_{SS}(f))I\right] = IFFT\left[1(f)H_T(f))\right] = IFFT\left[1(f)\right] * IFFT\left[H_T(f)\right] \tag{1.10}$$

Thus, in TD the driving function will be $\mathrm{sinc}(t) = \sin(t)/t$, having high sidelobes. To reduce the sidelobes the equalized signal should be windowed in FD by using a Gaussian window W. Consequently the object backscattered signal $h_{exp}(t) = IFFT\left[S \cdot I \cdot W\right]$.

4. UWB Antenna characteristics

By described methodology the UWB antenna should produce a linear-polarized radiating field with linear phase shift in FD and should have minimal pulse distortion in TD. Apparently for efficient LTR analysis suppressed ringing is required.

The properties of two linear-polarized antennas were investigated in order to ascertain their ability to transmit the pulse with suppressed own ring. Two Vivaldi antennas as well as dual-polarized diagonal horn antenna [6] were measured by means of the two-antennas method. In our experiment we used a signal with 5.3 GHz bandwidth (0.18 ns pulse). After the signal pre-processing TD responses were calculated (Fig 3), there is damped ringing within duration of 0.1-0.2 ns for both antennas. However in the case of the horn, the clear distortion of the pulse itself as well as a significant ringing and multiple re-reflections make it less attractive for our purpose. This is due to masking of the useful LTR signal if the parameters of the ring signal coincide with those interrogating the target.

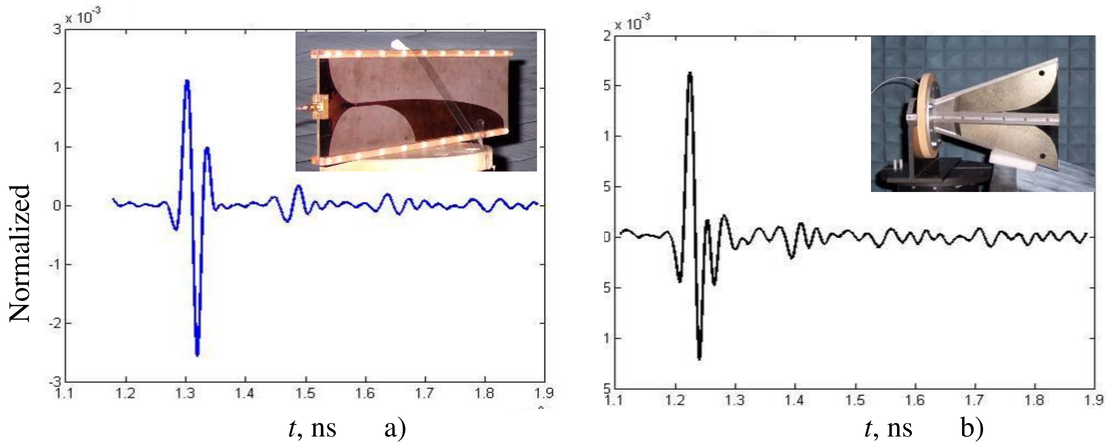
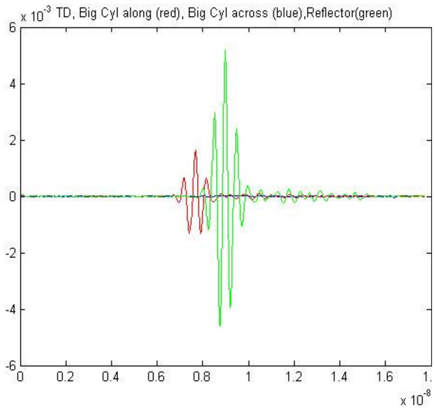


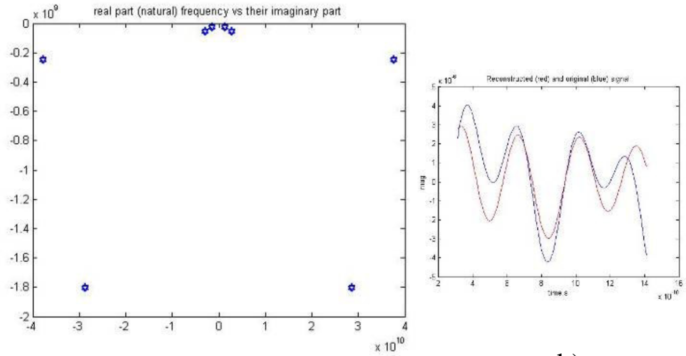
Fig. 3. time-domain waveform of the Vivaldi Antenna a) and Dual-polarized Horn Antenna b)

5. Results and Discussion

The measurements were accomplished for various targets in the frequency band 1 GHz-5GHz. Distance between co-located Vivaldi antennas is 1 m and the distance between antenna and target is around 1.6 m. The limited size of this paper only allows presentation of illustrative materials. Fig. 4 shows the responses of three canonical targets (cylinder across polarization, cylinder along polarization, metal sheet) which, generally speaking, may be considered as the main constituents of body-CW&E system. These serve our purpose to distinguish small objects (cylinder, sphere) on the background of a conducting sheet (rough approximation of human body). It is easily seen that response from cylinder across polarization demonstrates smaller amplitudes and for low SNR could be masked by noise. Thus changing the polarization of interrogating wave enables more confident selection of useful LTR tail. As it was shown before [1] small objects set against large masking ones can be resolved by using this approach.

Extracted poles and residues for 3 cm radius sphere are shown in Fig. 5 a)-b). In the case of the conducting sphere the lowest transition resonance corresponds to the lowest TM resonance of the sphere. Within the original notation of Stratton's book [5] the lowest resonance characterizes by $\rho = \pm 0.86 - i0.5$, where $\rho = ka = 2\pi a/\lambda = C/\lambda$ and C is the length of greatest circumference of a sphere. Lowest quasi-resonant TE and TM modes are excited during the time when incident wave reaches and scatters on the sphere.





a) b)

Fig. 4. TD equilized and substracted signals of cylinder along **E** (red), cylinder across **E** (blue), sheet (green)

Fig. 5. Set of extracted frequencies for the 3 cm radius sphere a)reconstructed by 3 modes (red) signal and original (blue) LTR signal

Theoretical and calculated natural frequencies correspond to the following complex frequencies:

$$f_{teor} = (1.368e9\text{-}7.952e8i \quad 1.368e9\text{-}2.386e9i \quad 1.384e9\text{-}3.451e9i \quad 2.783e9\text{-}2.974e9i \quad 2.879e9\text{-}1.113e9i)$$

$$f_{PoF} = (\pm 1.47e9{+}2.79e7i \quad \pm 2.9e9{+}5.58e7i \quad \pm 2.8e10{+}1.80e9i \quad \pm 3.70e10{+}2.46e8i)$$

Let's stress that all transient modes are highly attenuating and could be characterized by pronounced evanescent behaviour. It is easily seen that the lowest retrieved frequency is nearly the lowest theoretical value and in keeping only a few significant poles in the retrieval procedure we will obtain the modes sorted by the smallest attenuation. Discrepancy of the imaginary parts could be explained by slow attenuation of the measured modes during scattering on a non-perfect sphere.

Currently we are investigating typical target response (hand grenade, small gun, mashine gun) in free space and on the human body, as well as physical aspects of human body influence on target resonant response; the results will be presented at the conference.

Conclusions

The feasibility of small target detection against the human body has been proven. It has been demonstrated that the efficiency of the detection depends vitally on the TD characteristics of the transmitting and receiving antenna.It has been shown that the algorithm of pole and residue retrieval should be based on the fundamental physical frequencies rather than overall signature analysis.

The improved signal preprocessing and pole retrieval algorithms have been suggested and validated. Theoretical solution, full-wave modeling and initial experiment have been implemented for simple targets and good agreement between results demonstrated the usefulness of the suggested approach.

Acknowledgment

The work reported in this paper is funded by EPSRC UK IP/DO32652/1.

References

[1] M. S. Gashinova, M. Cherniakov A. Vasalos, "UWB signature analysis for detection of body-worn weapons," Proceeding of 2006 CIE International Conference on Radar, Shanghai (China) 16-19 October, vol.. II., pp.1450-1453, 2006

[2] Y. Hua, T.K.Sarkar, "Generalized Pencil-of-Function method for Extracting Poles of an EM System from Its Transient Response", IEEE Trans. On Ant. And Prop., vol.37, no..2, February, 1989

[3] C. E. Baum, "On the singularity expansion method for the solution of electromagnetic interaction problems," Air Force Weapons Laboratory, Kirtland AFB, N.M., Interaction Note 88, Dec. 1971

[4] M.Cherniakov, A. Vasalos, Pedestrian Recognition via Ultra wideband (UWB) Radar , International Workshop on Intelligent Transportation – WIT 2005, Hamburg, Germany, Proceedings pp 95-99, 2005

[5] A. Stratton: Electromagnetic Theory, New York: McGraw-Hill, 1941

[6] http:// www.ets-lindgren.com/productpage.cfm/model/3164-04/producttype/Antennas