Multi Object Concealed Threat Detection by Late Time Response Analysis

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***Abstract*— A new approach has been considered to detect threat item among multiple concealed objects by analyzing the delayed time- response of the objects, that would be illuminated by an ultra wide band radar. It was observed that the reflected wave, from the target, produced a delayed damped sinusoidal oscillation, that contained aspect independent complex natural resonances, which was unique for any individual object. A generalized pencil of function is applied for signal processing to extract poles from the scattered late time response of different objects. Application of hamming window function improves discrimination and detection of poles of multiple objects. Determination of the presence of a particular pole or concealed threat is observed upon using this proposed methodology.**

***Keywords— late time response, complex natural resonance, generalized pencil of function, UWB antenna, hamming window*.**

I. Introduction

The incidents of armed attacks on innocent masses at secured areas or any public gathering has been on the rise. Which is why, it is of utmost requirement that a robust security be developed, that is able to detect and discriminate the concealed threat items such as small hand-guns, knives, and those items that are easily hidden under clothing. The existing technology makes use of metal detectors which uses the technology of ionizing, in order to detect metallic substances with precision. But this system has the limitation of not recognizing non-metallic threat items or to detect threat items only among various non- threat items. Millimeter wave scanner applies imaging technology to detect the concealed items but this approach is time consuming and leads to the problem of privacy intrusion and health-affecting issues [1].

One other safer approach can be adopted by using a non-imaging millimeter wave radar for scanning. The radar beam can easily pass through clothing though it is opaque to plastics or certain metals, that reinforce suitable selection for conceal threat detection [2-5]. A higher frequency 'W' band system has already been developed for detecting concealed weapon and dielectric material explosives[6].

In this paper, a potential method has been adopted for detection of concealed threat among different objects by investigating and analyzing the characteristics of complex natural resonances of the radar scanning of various items. It was observed that when an object is excited by microwave signals, from a UWB radar, the back scattering from the object, produces an exponentially decayed sinusoidal response. This response contains Early Time Response (ETR) which is the immediate return from the target, and the Late Time Response (LTR), delayed returned signal. LTR is the aspect independent time response, which is characteristically unique to the object[7-10] .The excitation energy required to illuminate any concealed object at radio frequency is less than the standard safety level with respect to human exposure to RF signals, therefore this method is safe for health related issue[11] . Among the few signal processing methods of extracting the CNR poles from LTR analysis, Prony's method with singularity expansion method (SEM) is commonly used[12-14]. This method is extremely vulnerable to noise and complicated procedure. Hence a reliable method, generalized pencil of function (GPOF) which is least sensitive to noise and easy to compute is used for pole extraction from LTR [15,16].

The LTR of single object contains poles of same object only, hence detection of concealed threat is more deterministic. LTR analysis of multiple objects is a complicated one as the response contains noise along with the multiple poles from different objects. Therefore a thorough detail analysis is required to find out the potential threat among them. Emphasizing the detail analysis of important area of the response, hamming window function is applied along with GPOF algorithm[17]. The outcome showed, pole characteristics from LTR analysis of multiple objects using the proposed methodology for distinguished different objects and detecting concealed threat is very much effective.

II. LTR of Multiple Object Using GPOF Method and Hamming Window

A conductive object is excited to its complex resonance frequency by an UWB frequency radar, then the returned signal from the target contains aspect independent complex poles which depends on the geometrical shape and material of the object. The back-scattering of the target is transient LTR which is the sum of exponentially damped sinusoids and can be expressed as [13,14]

$$S[n] = \frac{1}{2}\sum_{M=1}^{M}\left(C_m \exp(Z_m n\Delta t) + C_m^{*}\exp(Z_m^{*} n\Delta t)\right) + N[n]$$
(1)

The returned signal 'S' is sampled at Δt time interval from the LTR. Model order M is the upper summation limit to represent the target properly, determined from the pole frequency, the complex natural resonance $Z_m = -\alpha_m + i2\pi v_m$, is the combination of aspect independent component, damping factor α_m and oscillation frequency v_m, which is unique to the object depending on shape and material. Noise N corrupts the signal, mostly generated from the background clutter and electromagnetic reflection from other substances. The complex amplitude C_m is aspect dependent and varies according to orientation of illuminating pulse. In practice, it has been observed that only the first few lower order modes of CNRs have sufficient amplitude and are useful to identify any object, and the subsequent higher order modes suffers from low amplitude, that decay very rapidly.

The LTR signal is collected from the VNA has transformed into time domain by inverse Fourier transform for extracting the poles using GPOF algorithm. GPOF is a mathematical method used to extract poles by solving generalized Eigen value problem. The performance of GPOF depends on model order number. Complex object pole detection required higher model order. High model order produces many poles at the output. Hence, to identify the poles of threat among various objects, hamming window function is used that aids to filter out spurious poles at the output.

III. METHODOLOGY AND RESULTS

The experiment was conducted using two double ridge horn antenna in a pseudo-monostatic radar arrangement. A vector network analyzer (VNA) in association with the antennas was used to produce UWB stepped frequency-modulated continuous wave radar signal with operating frequency ranging from 0.3 GHz to 3 GHz. The VNA is set to the power level 2dBm and 50 cm distance was maintained between the target and the antenna, in a not anechoic environment, for all the experiments. The multiple objects taken for the experiment were constituted of a small replica pistol, a steel rod and a mobile phone. In the first set of experiments, every object was placed individually. The second set of experiments was performed by the grouping of two objects touching each other side by side. In each experiment, objects were scanned ten times and respective averages were taken to reduce noise effect. The measured data was collected from the VNA and transferred to a computer for post-signal processing using Matlab software. At the first step of data processing, the measured response in frequency domain was changed into time domain signal by applying Inverse Fast Fourier Transform (IFFT). For focusing and reducing noise in the frequency zone of interest, windowing operation was performed using hamming window. The LTR was taken from the scattered time signal and GPOF algorithm was applied to extract the pole, or CNR, and the residues, or complex amplitude of the LTR. The number of poles or model order, a critical parameter, was estimated by pole filtering and standard error calculation of reconstructed LTR for different model order, ranging from 1 to 10.

In the first experiment, a 15 cm steel rod was taken as the target, that was illuminated by the UWB radar signal. The extracted poles from the LTR of the target provided resonance around 0.864 GHz, as shown in Fig.1. The complex natural resonance frequency of the target can be predicted by $F = \frac{C}{2L} \times A$, where 'L' is the length of the target, 'C' is the velocity of light and 'A' is a dimensionless parameter depending on size of the object, 0.85 is considered for this experiment. Using this theoretical prediction , pole frequency of the 15 cm steel rod was predicted to be around 0.850 GHz, which was very close to the experimented value .

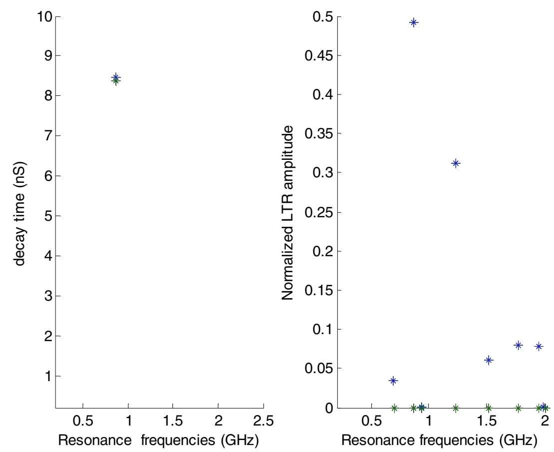

Fig.1. LTR frequencies and their respective decay time and amplitude of 15 cm steel rod.

Similarly, the pole frequency for a replica pistol and a mobile phone was measured at 0.728 GHz and 0.922 GHz respectively.

In the second set of experiments, the replica pistol and the mobile phone were placed together, in contact, as "multiple object" and was illuminated by the UWB signal. It was evident from the LTR analysis of the return signal that the response was most crowded in the two frequency regions at around 0.714 GHz and 0.885 GHz, as shown in fig.2.

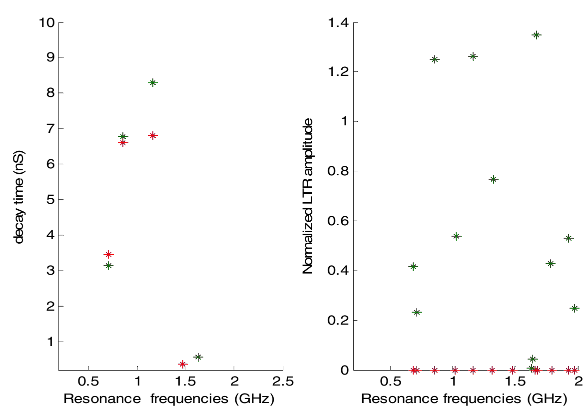

Fig.2. LTR frequencies and their corresponding decay time and normalized amplitude of the mobile phone and of the replica pistol placed together

To successfully perform multi object identification using GPOF method requires higher model order. The model order showed more numbers of poles at the LTR as shown in fig.3

for the response of steel rod and replica pistol in contact with model order 6. From this response it was noticed that clustering of poles can be found around 0.735 GHz and 0.845 GHz with other spurious output. When LTR is processed with the same data using hamming window and GPOF method, some of the spurious poles due to noise got inhibited and produce more clear response at 0.745GHz and 0.856GHz as shown in fig. 4.

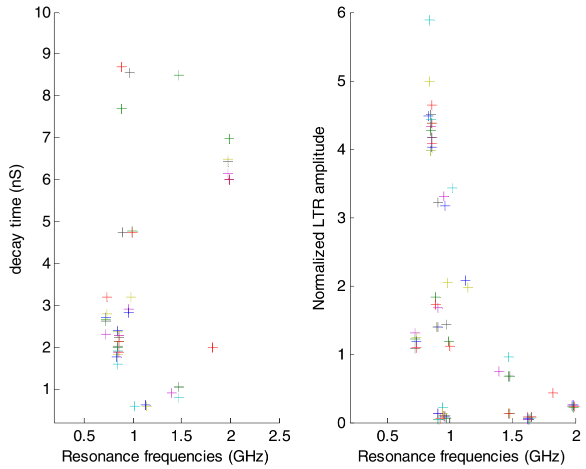

Fig.3. LTR frequencies and their corresponding decay time and normalized amplitude of the steel rod and of the replica pistol placed together using GPOF method only

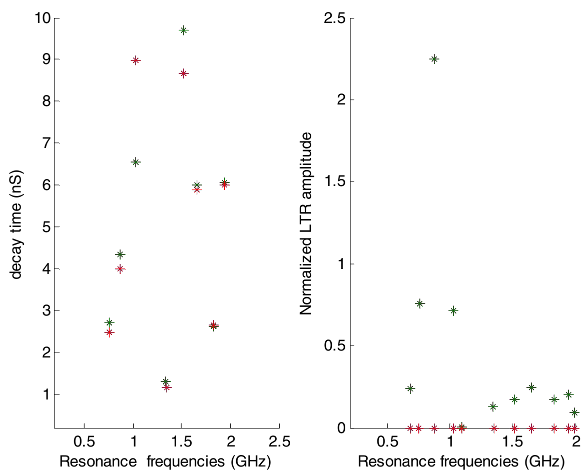

Fig.4. LTR frequencies and their corresponding decay time and normalized amplitude of the steel rod and of the replica pistol placed together using GPOF method and hamming window function

DISCUSSION AND CONCLUSION

It was observed that the complex natural resonance from LTR of any conducting object is unique as it is aspect independent. It was also observed that when multiple objects are placed in closest proximity of each other, the LTR shows existence of the multiple objects. The presence of poles at different regions in the LTR proves the existence of different objects and after analyzing the result, each item could be identified. In case of multiple object analysis, it was noticed that the values of fundamental frequency of CNR was slightly different from that of a single object, as mentioned before, that the CNR frequency of the replica pistol is 0.728GHz and mobile phone 0.922GHz respectively when they are placed individually. But when those items are kept together, they originated clustering of poles around 0.714 GHz and 0.885GHZ. This shift in the resonant frequency of the poles of multiple objects are due to the closeness of the objects(less than 8 cm). The proximity of the objects develops the interaction of the induced electric fields so that they resonate as a composite object, as opposed to that of two individual items. The pole extraction from LTR suffers from the problem of noise from background cluttering and reflection from other substances, therefore at the output, many poles' presence was observed and the numbers kept increasing with higher model order, as shown in fig.3. To reduce such effect and for a detailed analysis in the interest frequency range, hamming window function was applied, so that the spurious pole existence at the output was reduced, as shown in fig.4.

Thus, it is apparent from the experiment, that identification of threat among multiple objects is possible within a radar beam using a proper range resolution method. A more fine-tuned detail of CNR is possible by application of phased array antenna and if proper anechoic environment is maintained. To ensure accurate threat identification, further research and work will be required to use machine learning algorithms, in order to classify the objects.

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