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A Radio-frequency Measurement System for Metallic Object Detection Using Pulse Modulation Excitation

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Abstract

Guns and knives have imposed a significant threat to public safety. Based on the electromagnetic characteristics of the materials of guns and knives', techniques concerning Electromagnetics (EM) e.g. walk-through metal detection equipment and X-ray and THz screening system have been used in an effort to detect and characterise them. Different EM frequencies for metallic object detection have demonstrated different merits. This paper reports the ongoing investigation of RF measurement for metallic object detection using pulse modulation excitation which consists of multiple frequency harmonics with the centre frequency varying within 1-12 GHz. The frequency response and resonance frequency behaviour of object position, object shape, rotation and multiple objects have been tested and analysed. A system utilising the pulse-modulated RF mode and sweep-frequency mode has been set up to implement sensing of metal items at a standoff distance more than 1 meter. Through a series of experimental investigations, it can be found that the positions of the metal items have significant effect on the spectrum profiles of received RF signals. Such effect presents a modulation pattern in frequency domain, in consequence of which new features have been investigated in order to implement detection and characterisation of metallic objects.

Keywords: Radio frequency measurement, metallic object detection, Electromagnetics, Pulse modulation, Gun and knife detection

1. Introduction

The abuse of guns and knives has posed a significant threat on public safety. Subsequently it is crucial to tackle the issue before the threat takes effect. At the frequency range from a few hundred MHz to approximately 300GHz, the objects illuminated by the incident Radar-Frequency (RF) wave show a distinctive radar cross section (RCS) based on their natural resonance frequencies, depending on their dimensions, materials and shapes[1-3]. As a result, metal detection and screening techniques that use the radio/microwave boundary have gained a lot of attention for mitigating such threats. In contrast to the techniques using higher frequency ranges such as X-ray and THz imaging[4-7], radio/microwave screening techniques have advantages in terms of cost-effectiveness and a much simpler system setup.

Whilst they still realize the standoff distance detection, which hinders the approaches when using relatively low frequency electromagnetic waves/fields[8].

Multiple antennas have been adopted to implement the sweep-frequency detection in reflection configuration with the utilization of commercially available RF equipment, such as the frequency spectrum analyzer[3] and the vector network analyzer[9], knowledge-based approaches such as artificial neural network (ANN) and genetic algorithm were employed for object characterization and false-alarm reduction[3]. Single frequency and multiple frequency radar systems such as Ground Penetration Radar (GPR) system have been used for non-destructive testing and non-destructive evaluation (NDE)[10], and geophysical survey. K. C. Ho et al. used one-sided linear prediction in frequency domain along with maximum likelihood estimate to reduce the false alarm in detection of land mines[11]. T. Chan et al. extended the technique to two-sided linear prediction and experimentally proved that the proposed technique dramatically improves the detection efficiency[12]. Optical depth, as an essential feature of an emerging detection method, has been employed for the measurement of specific dimensions of concealed dielectric items at a distance. N. Bowring et al. have recently presented a millimeter-wave sensor to detect and measure thin dielectric layers in the field of millimeter wave spectroscopy[13, 14]. By either using the Fast Fourier transform (FFT) or the Burg transform of the acquired frequency spectrum from 14 GHz to 40 GHz, the optical depth shows quantitative correlation with the thickness of the dielectric object.

Pulse modulation RF wave (PMW) is adopted in missile radar systems to track and guide the missiles[15], and in the medical industry to analyze the formulations of drug products[16]. Since the carrier with a single frequency is truncated by introducing the wide-band pulse, multiple frequency harmonics centered on the carrier can be obtained in one RF emission process. This dramatically reduces the operation time in contrast to the Sweep-frequency RF wave (SFW). A significant advantage of PMW lies in the fact that the centre frequency of PMW is selectable and thus the distribution of RF power within the high-frequency band for measurement can be adjusted.

The rest of paper is organised as follows: Section 2 presents the details of the experimental system configuration and properties of the samples employed in the investigation. Section 3 reports the experimental results and discussion involving (1) the investigation of the influence of metal positions on the acquired RF spectrum; (2) RF measurement using PMW and its comparison with SFW. The summary and conclusion are drawn in Section 4.

2. Experimental Systems

Two experimental systems have been built and investigated for metallic object detection and characterization at standoff distances. The two systems have a similar system configuration but different mode signal projections (excitation): PMW and SFW.

The RF transmission-and-receiving module consists of a pair of wideband horn antennas working from 1GHz to 12GHz, one of which is used as the transmitter supplied with 20dBm RF excitation (generated by an Agilent E8267D PSG vector signal generator). The second horn constitutes the receiver. For the RF measurement using SFW, the microwave frequency is swept between 6 GHz to 12 GHz with 256 frequency steps. By applying the Eq. (1)[14]

presented below, the minimum resolution of the feature namely optical depth (OD) is computed as 2.5 cm, and thus the maximum is 3.2 m.

$$\Delta OD = \frac{C}{2\Delta \nu} \quad (1)$$

Where, ΔOD denotes a sample of optical depth; C stands for the velocity of light in vacuum; $\Delta \nu$ is the frequency bandwidth of the system, which is 6 GHz for the particular setup described here.

The RF measurement using PMW is conducted by setting the synthesizer to pulse-modulation mode to generate the PMW with a variable centre frequency f_c between 1GHz – 12GHz. In order to carry out the comparison of PMW with SFW, with respect to every f_c, the synthesizer is set to generate the SFW around f_c for SFW measurement. The maximum amplitude of each measurement is recorded by a 26.5 GHz spectrum analyser (Agilent E4440A) which is connected with the receiver. The schematic illustration of the systems is presented in Figure 1.

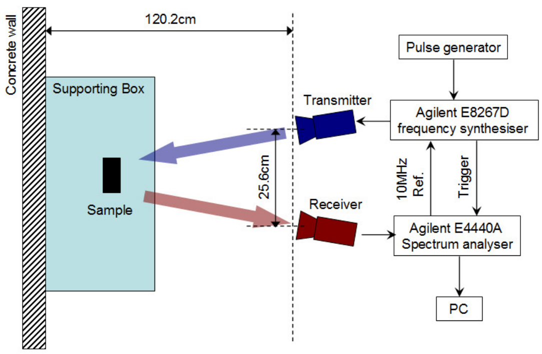


Figure 1. Schematic of experimental setup

The dimensions and electrical properties of the illuminated samples simulating the real gun barrels are listed in Table 1. During the test, they were placed on a box made of microwave absorbing foam of dimensions 49.5cm by 31.0cm by 98.6cm, which was placed right next to the wall. In the test, 6 positions were selected, starting from the edge of the supporting box (31cm away from the wall) and monotonically decreased at an interval of 5 cm along the symmetric axis of the two antennas.

Table 1. Dimension and electrical properties of metallic samples

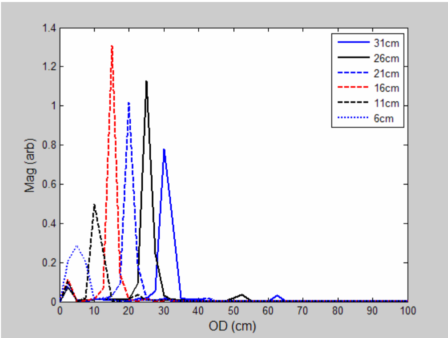
Sample	Length or Outer diameter (cm)	Width or Inner diameter (cm)	Height (cm)	Material
Pipe	3.4	2.7	14.9	Steel
Cube A	2.5	5.0	14.9	Al Alloy
Cube B	5.0	5.0	32.0	Al Alloy

3. Measurement results and discussions

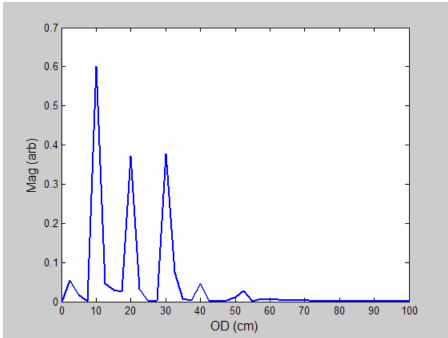
3.1 Dependency of RF spectrum on object positions

With the RF illumination region, the metallic objects show high reflectivity as long as the wavelength of RF incident wave is comparable to or smaller than the dimensions of the objects. The reflected waves from the object and the wall are superimposed and result in the modulated wave which is picked up by the receiver. A particular oscillation of the modulated wave can be found in the spectrum, and the frequency of the oscillation indicates the characteristics of the illuminated object.

The measurement is carried out firstly with SFW. Two cube samples are introduced for investigation of RF wave interactions with single object and multiple objects at different locations. For single-object case, Cube A is placed at 6 positions while Cube A and Cube B are deployed at 31cm and 21cm away from the wall respectively for multiple-object case. The analysis results based on the spectrum for each measurement are presented in space with x-axis representing the OD.



(a)



(b)

Figure 2. Spectrum analysis for OD against object positions: (a) single object; (b) multiple objects

From Figure 2(a) it can be seen that the ODs corresponding to the major peaks are directly proportional to the locations of the sample with respect to the wall. If the distance between the sample and the wall increases, the peak shifts positively along the x-axis which represents the optical depth. Inversely, the peak shifts negatively with the distance decreases. It is also note worthy that the values of these peak-corresponding ODs (5cm, 10cm, 15cm, 20cm, 25cm, 30cm) have good agreement with the real distances (6cm, 11cm, 16cm, 21cm, 26cm, 31cm) between Cube A and the wall. The discrepancy is believed to result from the small resolution of the current RF system, ±2.5cm which indicates that the system can hardly distinguish the two reflectors with distance interval of 2.5cm.

Interestingly, as can be seen in Figure 2(b), there are 3 significant peaks occurring within the OD range up to 100cm. The ODs corresponding to these 3 peaks are respectively 10cm, 20cm and 30cm. These values also have good agreement with the real distances 10cm, 21cm and 31cm, which indicates that the measurement result can be used to quantitatively determine 3 distances: the distance between Cube A and the wall; the distance between Cube B and the wall; the distance between Cube A and Cube B.

From the experimental results, it can be seen that with the secondary reflector i.e. the wall introduced within the RF illumination region, the RF spectrum is highly dependent on the relative location of the metallic objects with respect to the wall. It is because of the fact that the RF resonance takes place between the two reflectors when they get illuminated by the incident RF wave. The finding contributes to the RF measurement using PMW. Since PMW has wide frequency band and the measurement using PMW is analogous to SFW with predefined band, therefore the position of the object should also influences the spectrum acquired using PMW.

3.2 Comparison of PMW with SFW

PMW is actually a special case of Amplitude Modulation (AM). The carrier normally sinusoidal wave with variable centre frequency (f_c in GHz) is gated at a pulse rate. As a result, the PMW has sidebands in the frequency spectrum at $f_c \pm n f_m$ (where f_m denotes the pulse repetition frequency). If the pulse is a rectangular pulse, thus the magnitude for each frequency component can be analytically written as[15, 17]:

$$a_n = 2A \frac{\sin(\frac{n\pi\tau}{T})}{n\pi} \tag{2}$$

where, τ denotes the pulse width (PW); T and A stand for the pulse period (PP) and the amplitude of the rectangular pulse, respectively.

It can be found that the spectrum of PMW is dependent on the PW, PP and f_c. During the PMW RF measurement, the parameters are set as follows: PW=120ns; PP=140ns. The centre frequency of PMW is chosen as 4GHz, 6GHz, 9GHz, and 12GHz. It has been found that the spectrum of PMW can effectively cover 1GHz band from the initial experiment by making the two horns facing each other to implement direct antenna coupling. As a result, the observation window is 1GHz, and the spectrum amplitude outside the window is masked by the noise and not applicable to the signal processing.

The raw signals from PMW and SFW measurements are shown in Figures 3. Please note that before each metallic sample is introduced within the illumination region, the background spectrum (BG) is obtained and presented in each sub-figure for individual f_c.

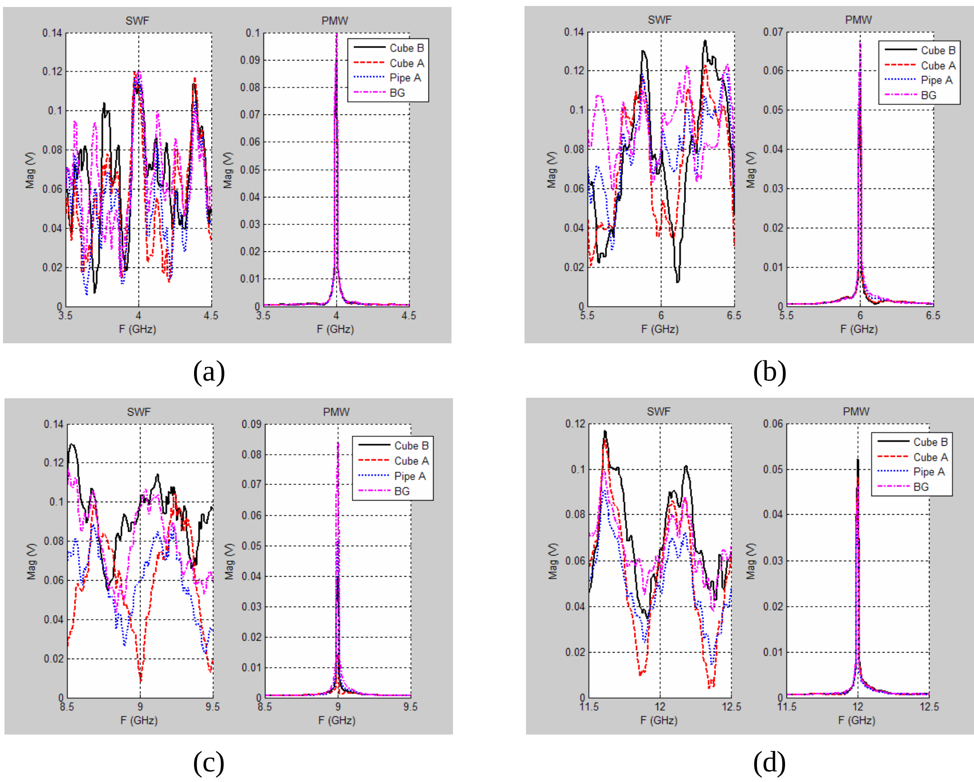


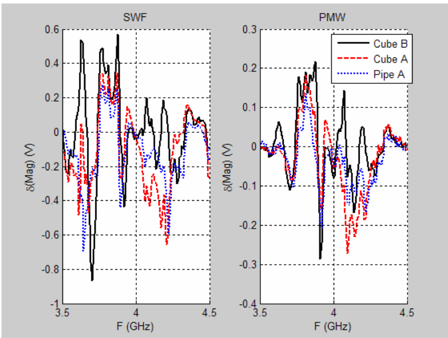
Figure 3. Measured spectrums for PMW and SFW with respect to centre frequency set at: (a) 4GHz; (b) 6GHz; (c) 9GHz; (d)12GHz

It can be noticed from Figure 3 that the acquired spectrum profiles of PMW and SFW have distinct trajectories, which is due to the difference of the intrinsic characteristics in PMW and SFW. For SFW the power is evenly allocated to each frequency components while as for PMW most power is concentrated around the centre frequency and attenuates in an exponential manner as frequency components moving further away from the centre frequency. Consequently it is of necessity to apply signal processing method to unveil the correlation between PMW and SFW.

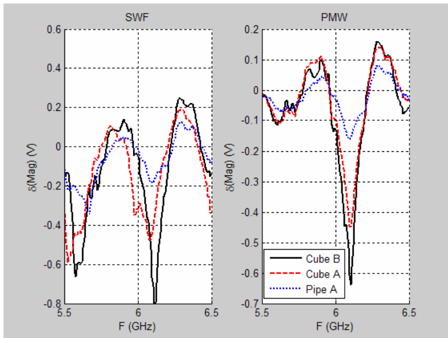
Here, a normalisation-and-differential method is proposed particularly for spectrum analysis of PMW. The method implements the computation of normalised differential spectrum by subtracting the spectrum for BG from the measured spectrum for each object. The derivation of the normalized differential spectrum can be mathematically written as:

$$\Delta X_i = \frac{a_i - b_i}{a_i + b_i} \qquad (i=1, 2, 3, 4 \ldots n) \qquad (3)$$

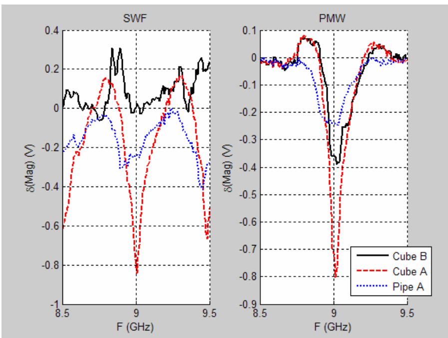
where, ΔX_i denotes the normalized differential spectrum; a_i and b_i represent the individual spectrum amplitude for each object and BG, respectively. Figure 4 presents the comparison of normalised differential spectrum between PMW and SFW.



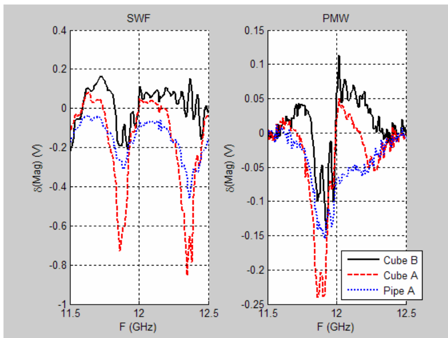
(a)



(b)



(c)



(d)

Figure 4. Normalised differential spectrums for PMW and SFW with respect to centre frequency set at: (a) 4GHz; (b) 6GHz; (c) 9GHz; (d)12GHz

Because the metallic objects with different dimensions show various reflectivity with respect to the incident RF wave with different frequencies (wavelength), therefore the obtained frequency spectrum of reflected RF wave indicates the properties of the illuminated items. As can be seen from Figure 4, the normalised differential spectrums of the 3 samples show distinct localised trajectories and features which can be used to characterise the metallic objects, though the overall profiles are similar due to the positions of the samples with respect to the wall are the same.

With respect to the same metallic object, it is noticeable that after normalized differential processing, the normalized differential spectrum distributions of PMW and SFW are similar, particularly in showing the oscillation due to resonance responses. The magnitude of PMW is approximately half the magnitude of SFW, due to how the radiation power is allocated to the individual frequency harmonics within PMW, which is noticeable in Figures 4. Since the RF reflection from the wall is taken into consideration, the oscillation found in normalized differential spectrums implies resonance due to the wave interaction between the object and the wall. It can be seen that in Figure 4 the ‘frequency’ of the oscillation is similar in terms of spectrum profile, particularly the distribution of resonance frequencies, which gives the indication of the position of the object with respect to the wall.

Nevertheless, it is worth noting that at the edges of the observation window for PMW in particular, the normalized differential spectrum of PMW has a large discrepancy compared to that of SFW. The reasoning lies in the fact that the magnitude of the spectrum for PMW at the window edges is nearly zero and thus the oscillation due to resonance is barely seen and should theoretically be zero. The observation indicates that even though the proposed method to calculate the normalized differential spectrum shows similar resonance oscillation within the PMW spectrum for an object, the modulation effect which results in high a magnitude around the centre frequency while nearly-zero amplitude at the window edges still influences the processed results.

4. Conclusion

Driven by the demand of detection of dangerous metallic objects such as guns and knives at standoff distance, an RF metal sensing system is set up with operational frequency band from 1GHz to 12GHz, and outward power of 20dBm. Two RF stimulation modes are implemented in the system: PMW and SFW. This paper presents the results of phenomenology investigation of RF interaction and response to different metallic samples using PMW and SFW. It can be found that with introducing the secondary reflector right behind the object under interrogation, the position of the object has significant influence on the acquired spectrum. Under current system configuration, the object position can be estimated with discrepancy less than 2.5cm by using SFW.

The research reported in this paper has presented that by applying the proposed algorithm, PMW has been found equivalent to SFW in normalised differential spectrums with respect to the same metallic item under illumination. Since PMW has a wealth of frequency harmonics, especially within the predefined observation window of 1GHz (depending on the RF power), it has shown advantage over SFW in acquiring the spectrums with respect to different objects, and characterising the illuminated metallic objects in terms of estimation of the positions, natural resonances due to different geometries as well as materials and the apparent reflectivity of metallic surface.

In light of the merits of PMW, further work will involve: (1) signal processing method for suppression of the intrinsic modulation effect on acquired spectrums using PMW; (2) investigation of feature extraction techniques for object identification involving structural and material properties (permeability and permittivity) using PMW measurement; (3) experiments with real/replica guns and knives.

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