Analysis of Crack Detection in Metallic and Non-metallic Surfaces Using FDTD Method

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Abstract. The use of microwave techniques for crack detection in metallic and non-metallic surfaces is a forerunner method. In this method, the reflection of incident wave to a cracked surface has been considered and from the characteristics of the reflected wave the crack can be detected. In our research, the interaction between crack and an ultra wide band pulse as an incident wave is simulated by FDTD (Finite Difference Time Domain) method and the reflected wave is stored and analyzed in time domain. FDTD is a space-grid time domain technique that directly solves the Maxwell's curl equations. This method is based upon volumetric sampling of the unknown electric and magnetic field within and surrounding the structure of interest and over a period of time. Where the modelled region extends to infinity, Absorbing Boundary Conditions (ABCs) are employed at the outer lattice truncation planes which ideally permit all outgoing wave to exit the region with negligible reflection. With FDTD method the cracks of arbitrary shape in metallic and non-metallic surfaces can be simulated. Even if the crack is coated with a thin layer of dust or paint, it can be distinguished with this method. The crack dimensions can be determined from the characteristic of reflected wave. The method was used for the simulation of some cases. The accuracy of the presented model is checked by some analytically solvable cases.

1. Introduction

One major deterioration source in metallic and non-metallic structural elements is initiation and growth of fatigue cracks. Undetected active fatigue cracks in structural elements under service loads are possible and could result in unstable fracture and catastrophic final failure of the structure under consideration. Non-destructive testing is the use of physical methods which will test materials, components and assemblies for flaws in their structure without damaging their future usefulness [1]. Nowadays many different techniques are used for non-destructive testing such as penetrating, magnetic particle, eddy current, radiography, leak, dynamic, acoustic emission, thermal and many other testing. Each of them has some advantages and some limitations. For example eddy current can not be used for non-metallic surfaces. There are several electromagnetic techniques that can be used to detect surface cracks. One of the NDT advanced methods is Ground Penetrating Radar (GPR). GPR is a powerful detection tool in many areas such as geophysical respecting, archeology, civil engineering, environmental engineering and military technologies as a nondestructive sensing tool [2].

Any GPR system includes the transmitter and receiver antennas (Fig. 1). The transmitter emits a precisely timed, very short pulse of low-power, radio frequency (RF) energy. The transmitted pulse is radiated downward by the radar antenna into the specimen

[3]. A portion of the RF energy is reflected wherever there is a change or discontinuity in the dielectric properties of the media. The remaining energy propagates through the boundary. The amplitude of the signal reflected from and through the boundary depends on the relative dielectric difference between the materials at the boundary. RF reflections or radar target echoes picked up by the antenna, coupled into the receiver, and processed for display, recording, and deterioration detection.

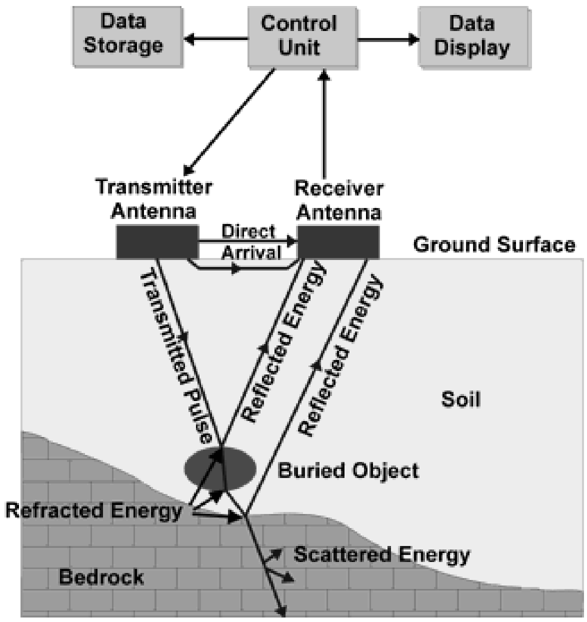


Fig. 1 Geometry of the GPR system

For simulation of this technique, the Finite Difference Time Domain (FDTD) method has been employed. This method is the most compatible numerical technique in the analysis of GPR systems and subsurface scattering mechanisms. The reason for this convenience is the easy modeling of the multilayer problem space and large number of different media embedded in it. In FDTD modeling the time information of the magnetic and electric fields are available. Absorbing boundary conditions are necessary to keep outgoing E and H fields from being reflected back into the problem space. For better results, the Perfectly Matched Layer is used.

In this study, a dipole antenna is used for transmitting and receiving the pulse. After that, by FDTD modelling, the impedance of the dipole is calculated for each point over the testing area. The impedance changing over the crack identifies the crack position and its dimension.

2. The proposed method

In this research, FDTD modeling is used for an antenna over a metallic or dielectric media. The dipole antenna scans all over the cracked surface and in each point, the impedance of antenna is calculated by numerical modeling. Distance between the antenna and the surface of the media is assumed to be equal all over the time of test. For impedance calculation, first the antenna is excited by a voltage source. Then the magnetic fields around the antenna is calculated and saved for each time step. The current of antenna is extracted from magnetic fields. The voltage and current of the dipole antenna at each time step were stored. After the end of FDTD loop, the voltage and current for a specified frequency was obtained from Fourier transform.

$$V(f_0)=\sum_n V(n\Delta t)e^{-j2\pi f_0 n\Delta t} \tag{1}$$

$$I(f_0)=\sum_n I(n\Delta t)e^{-j2\pi f_0 n\Delta t} \tag{2}$$

By dividing these two quantities, the impedance is calculated.

3. FDTD Method

The Finite Difference Time Domain (FDTD) approach used to model GPR, is a numerical method that provides a solution to Maxwell's equations, expressed in differential form in the time domain. The method, originated by Kane Yee [4], is based on the discretization of the partial derivatives in Maxwell's equations using central differencing. The E and H fields are assumed interleaved around a cell whose origin is at the location i, j, k. Every E field is located ½ cell width from the origin in the direction of its orientation. Every H field is offset ½ cell in each direction except that of its orientation. The resulting difference equations are used in a time marching iterative procedure to obtain the required solution [5]. Since the appearance of Yee's original paper, the FDTD method has been widely used in the solution of a diverse range of electromagnetic field problems such as radar cross section estimations, EMP coupling to dielectric structures, antenna modeling, electromagnetic field penetration, propagation in plasma and biological applications. A detailed review of the FDTD method can be found in [6]. In all models presented here, all media are considered as linear, passive and non-magnetic.

The simple GPR unit depicted in Fig. 1 contains a transmitting and a receiving antenna. The GPR unit travels above the ground-air interface, at a fixed elevation. The transmitter (T) generates the fields, which propagate toward and penetrate the ground with a particular polarization. The receiver (R) collects and samples the fields with the same polarization.

For numerical modelling in this research, a dipole antenna for transmitting the incident wave is used and then the impedance of the dipole antenna is calculated.
The time variation of the voltage source is given by:

$$J(t)=-\frac{2}{\nu}e^{\nu/4}e^{-\frac{(t-\chi)^2}{\nu}}(t-\chi)) \tag{3}$$

This is the first derivative of the Gaussian function normalized to unity. In this formulation $\nu=\frac{1}{2\pi^2 f_0^2}$ and $\chi=\frac{1}{f_0}$. where f_0 is the center frequency of the pulse.

The absorbing boundary condition was introduced at the outer lattice boundary to simulate the extension of the lattice to infinity. In this study the PML were used [7]. The innovation of Berenger's PML is that plane waves of arbitrary incidence, polarization and frequency are matched at the boundary.

4. Results

For FDTD simulation, a dipole over a cracked surface is modeled by Yee cells. The schematic of the problem is shown in Fig. 2.

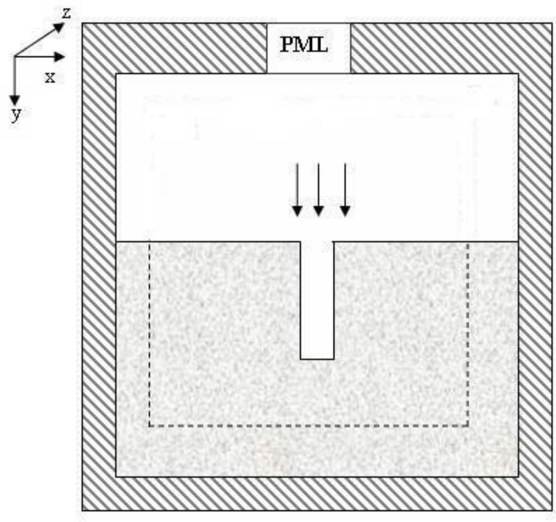


Fig. 2 FDTD simulation of the cracked surface

For each position of the dipole, the impedance is calculated after the end of the time loop of FDTD solution. The method for impedance calculation was discussed above.

At the first stage, a metal cracked surface is simulated. The crack was assumed to be long enough compared with wavelength. The crack has 1.2 mm depth with 0.6 mm width. The frequency used for impedance calculation is 20 GHz. It should be mentioned that the selected frequency is dependent to the crack dimension. For smaller cracks, higher frequencies are used. For this case a dipole antenna is located over the crack and it was parallel to the crack length. The impedance changing for all scan positions over the surface is shown in Fig. 3.

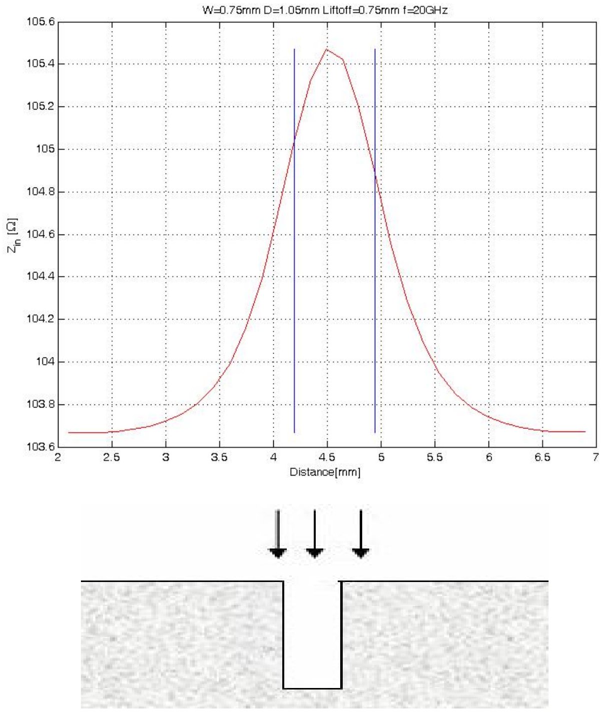


Fig. 3 Antenna impedance changing over a surface cracked metal

It can be illustrated that when the antenna becomes near the crack, the impedance increases. In additional, instead of impedance calculation, the reflected pulse from the surface can be obtained. By dividing the Fourier transform of reflected pulse to a Fourier transform of the incident pulse, a reflect coefficient for each point can be calculated. The reflect coefficient for the same crack as above is shown in Fig. 4.

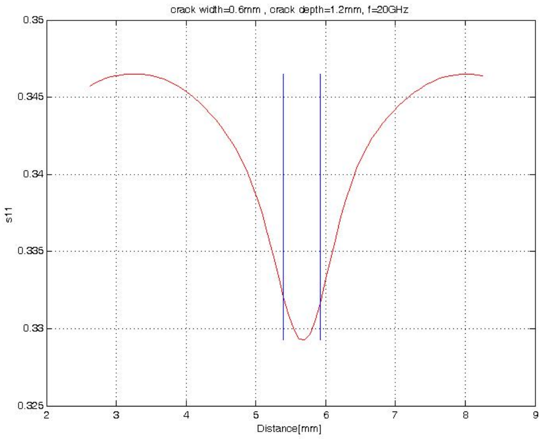


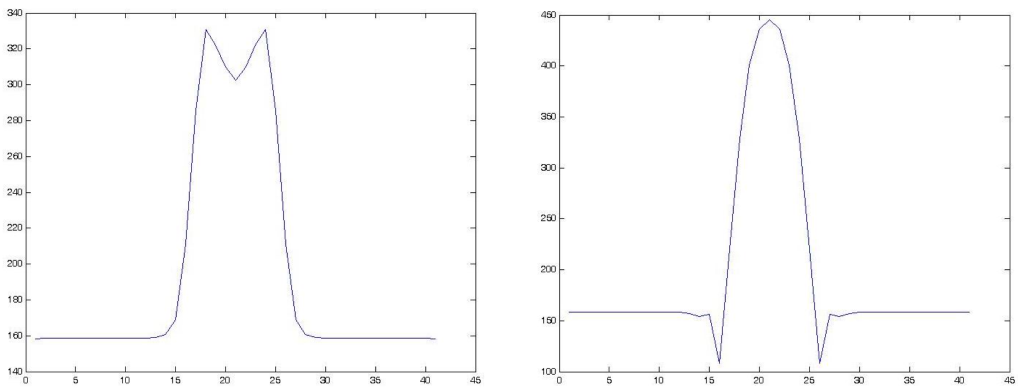
Fig. 4 Reflect coefficient changing over a surface cracked metal

As it is shown, the reflected coefficient decreases when the dipole becomes near the crack and in the middle of the crack the reflect coefficient minimizes.

For a dielectric surface, the same results can be obtained. In this case, even if the crack is inside the dielectric media, it can be detected.

The simulated crack in dielectric is a sphere hole with radius 2.5cm and is located 15cm under the media. The base media has $\varepsilon_r = 6$ and $\sigma = 0.01$ S/m. The selected frequency is 600MHz.

Fig. 5 shows the response to the air (dielectric) and conductor hole in the dielectric specimen in 600MHz. It is obvious that the response is frequency dependent.



(a) (b)

Fig. 5 Frequency response to (a) an air hole (b) a conductive sphere in the dielectric

For better recognition of the dimension of cracks, the effect of crack depth and width on the reflect coefficient diagram was considered. The results show that the output diagram depends on the crack depth and width. For a metal cracked surface with different depth and width, the output diagrams are shown in Figs. 6 and 7.

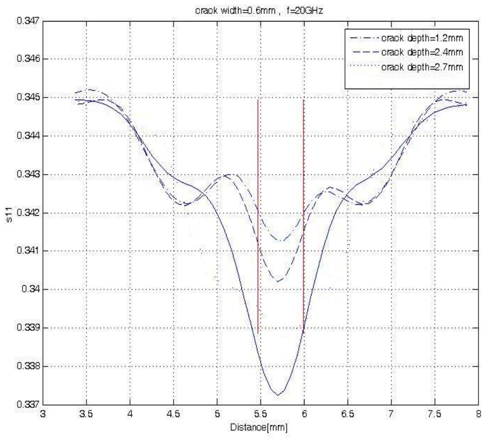


Fig. 6 Effect of crack depth

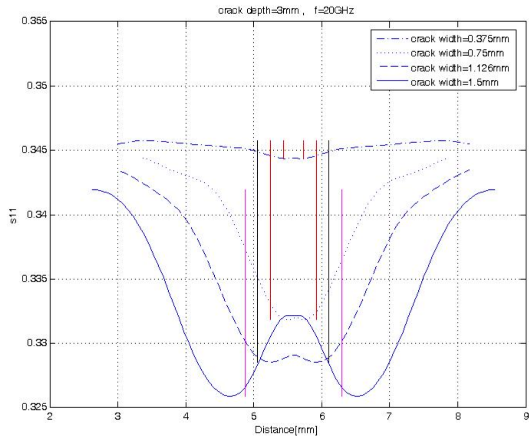


Fig. 7 Effect of crack width

By decreasing the crack depth, with the same width, the minimum of the output increases, as it is shown in Fig. 6. At the other hand, the deeper crack has more effect on the output.

Fig. 7 shows the effect of crack width for some cracks with the same depth. For the cracks that have less width, the difference between maximum and minimum is less, too. For wider cracks, instead of one minimum, two minimums and one maximum are appeared. The reason is, in this case the middle of the crack behaves as the flat surface and the output is going to be as same as the flat surfaces around the crack, so a maximum is appeared.

5. Conclusion

In this research, a recent method of electromagnetic NDT, was considered. In this method, an electromagnetic pulse emits to a surface and the reflected pulse received with an antenna. The changing in the reflected pulse shows the properties of the surface. Here, the interaction between the pulse and the cracked surface is modelled by FDTD Method. It is shown in both metallic and non-metallic surfaces, the crack can be detected. Also the crack width and depth affects the output reflect coefficient diagram.

6. References

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