Microwave Imaging Technique for Detection of Multiple Line Cracks in Concrete Material

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Abstract—**Nowadays, many concrete structures are exposed to higher loads than they are designed for due to the increase in human population and uncertain environmental conditions. This leads to a faster deterioration of the structure for example formation of cracks. Cracks provide significant signs for the health and residual strength of a civil structure. Though they appear at times in form of lines, they cannot be easily identified or detected by traditional methods and techniques. For example, manual inspection is too costly in terms of time and effort; meanwhile, other non-destructive techniques are bounded by each unique weaknesses. This research proposes a microwave imaging technique with ultra-wideband (UWB) signal in detecting multiple line cracks. UWB microwave signal offers a balance trade-off between resolution and cost as compared to other modalities. Various crack scenarios were first simulated using Finite-Difference Time-Domain (FDTD) to see the performance of the proposed technique. Delay-And-Sum algorithm (DAS) is used for image reconstruction. The technique was validated further through measurements of residential-grade concrete bricks with cracks using multiple P-shaped Wide-slot antennas. This technique was able to detect single, double, three and multiple line cracks on single brick of size 2 mm accurately. Notwithstanding, more than three cracks on a single brick could not be detected as they appears as a clutter. In conclusion, the proposed technique is useful for crack detection in building and man-made structures.**

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I. INTRODUCTION

Due to extreme events, structural buildings, bridges and other cement-based materials are often carrying more loads than they were initially designed. Consequently, their conditions deteriorate faster with time. Because of this, cracks are most of time seen on their surfaces. Cracks are types of damages that emanate because of surface breaking, delaminating and discontinuity to an existing structure [1].

There are several methods, which have been devised and used for crack detection in civil structures. According to [2] one of the most common techniques that had been used for crack detection is by manual inspection. In this technique, a specialist with a certain years of experience will inspect and note every detail information on the cracks, such as the location and dimension. The major drawback of this manual inspection includes (i) lacks of objectivity for quantitative analysis (ii) requires a lot of effort and (ii) time consuming. In addition, human inspection requires too many professionals for just a single task, it is financially restrictive [3]. Another down side is that two inspectors could give different results of distress information even when studying the same problem or defects. Several non-destructive evaluation techniques have been proposed and used for crack detection such as ultrasonic, vibration, and strain-based techniques, however, some of these techniques are ineffective, too expensive, high computational cost or need a combination of several techniques to achieve a single result [4].

The record progresses of microwave non-destructive evaluation technique imaging is obviously a fundamental fact to the importance of electromagnetic imaging within this high frequency band [5]. Numerous publications in the late 1980s and early 1990s foresaw the prospective and a growing field of applications in microwave sensing, particularly for non-destructive evaluation technique [6].

Radar imaging is an efficient tool for non-destructive evaluation and identification of the cracks. The technique has been improved via the understanding of the interaction between electromagnetic propagation and the electrical properties of concrete material leading to optimal radar measurement [4, 5, 7, 8]. Imaging concrete targets with wide band radar gave a 2D and 3D image with three different types of internal configuration [3, 9, 10].

Microwave frequency of 2 to 3.4*GHz* waveforms can adequately image concrete thickness measurement, whereas, 3.4 to 5.8*GHz* waveforms can detect delamination effectively, and 8 to 12*GHz* waveforms can sufficiently detect materials embedded inside a concrete. These frequencies served as optimal for the imaging of the respective concrete thickness, delamination and inclusions [11-13]. However, material characterization required an electromagnetic frequencies from 0.1 to 20*GHz* that can serve as a basis in applying wide band microwave imaging techniques for NDE of concrete using radar [14, 15].

Other related works in the literature reported the use of efficient inverse scattering electromagnetic imaging at various microwave frequencies, especially for 2D tomographic imaging approach [16]. However, the use of NDE can be implemented on the 2D tomographic imaging approach [17]. Detection of embedded objects, surface defects and tomography using stochastic optimization has been comprehensively reviewed and used in microwave imaging.

On the other hand, there was a giant breakthrough in microwave imaging procedure for detecting defects in dielectric structures which significantly saves long imaging reconstruction time; this was achieved by using hybrid genetic algorithm (GA) by pre-computing the Green's function for the configuration without defects [18]. Comparably, innovative inversion procedure centred on genetic algorithm were used alongside with Sherman–Morrison–Woodbury (SMW) matrix inversion method was investigated [19]. Likewise, the enhanced tomographic imaging using microwave signals was applied in cement-based materials for non-destructive evaluation. The technique utilizes the improved Sherman–Morrison–Woodbury formula for electric field computation [20]. In an effort to improve on non-destructive crack detection in civil structures such as bridges, some researchers tried to amalgamate the concept of electromagnetic, acoustic and elastic wave fields in imaging determinations [21].

Semi empirical model, X-band (8.2–12.4 GHz) frequency model was used with a probe. This method involves computing the reflection coefficient for both the starting and the middle point. The downside of this technique is that, to evaluate the reflection coefficient for these points, especially the middle point, an electromagnetic model need to be developed which may be difficult to design. Though another technique was also used by measuring the magnetic field around the device under test, the result shows that the calculated positions in the absence of crack was found to be correct, but in the presence of crack, the calculated position and the actual position does not agree which give rise to a broader distribution. This led to the introduction of a new parameter in order to be able to resolve this differences [22].

The performance of these crack detection techniques could be divided in to vital characteristics such as, crack precision, position, computational time, cost of measurement equipment and setup [23]. Therefore a very robust method is required that reduces the computational time, reconstruction technique that principally leads to qualitative images, and an enhanced data acquisition system which gives a highly precise position of the crack with less cost.

In this paper, a method aimed at reducing the burden of very long computational time while maintaining the precision of crack detection will be presented. In this case, the computation time and precision of the crack detection are the important factors in the crack detection analysis. In this work, a novel P-Shaped Wide-slot antenna array is used as sensor with ultra-wideband characteristic [24]. A PC with Labview is used for automatic extraction of the sensor values before applying Delay-And-Sum (DAS) algorithm for final image reconstruction. For validity and practical application of this project, a real brick phantom and a small model building structure was used in validating the method and procedures experimentally.

II. IMAGE RECONSTRUCTION WITH DELAY-AND-SUM BEAMFORMER

The Delay-And-Sum (DAS) algorithm was used for image reconstruction technique [25]. The equation is presented by Eq.1, where I denotes the energy at point x, m the transmitter number, n the receiver number, s the normalized and background subtracted measured signal, W the integration window size, and τ the propagation delay from the transmitter m to point x and to receiver n.

$$I(x) = \int_0^W \left[\sum_{m=1}^{M} \sum_{n=1}^{N} s(t-\tau) \right]^2 dt \tag{1}$$

The resolution, Δx of the beamformer is dictated by Rayleigh criteria as in Eq. (2) where ε and f_c are the permittivity and the central frequency respectively.

$$\Delta x = \frac{c}{2 \cdot \sqrt{\epsilon} \cdot f_c} \tag{2}$$

According to Eq. (2), the higher the center frequency, f_c, the higher will be the range resolution, Δx, which can be achieved. However, the maximum frequency is limited by the fact that at higher frequencies, the signal suffers from a higher signal reflection and attenuation inside the material [26]. Following several tests that was carried out, it was discovered that the optimum f_c is from 1 GHz – 7 GHz. Using this frequency bandwidth together with 16 antennas in multistatic configuration, $\Delta x = \lambda/14$ can be achieved as shown in later section.

III. RESULTS AND DISCUSSION

A. *FDTD-Simulation*

Most of the times, cracks cut through a civil structures is hardly visible from the exterior. This model tends to simulate and see the performance of this sensors and DAS algorithm in detecting cracks of different lengths and orientations. Figure 1 shows three different models, (a) one with a single crack (b) two unidirectional cracks and (c) three multidirectional cracks. The imaging results are presented side by side to each simulated model.

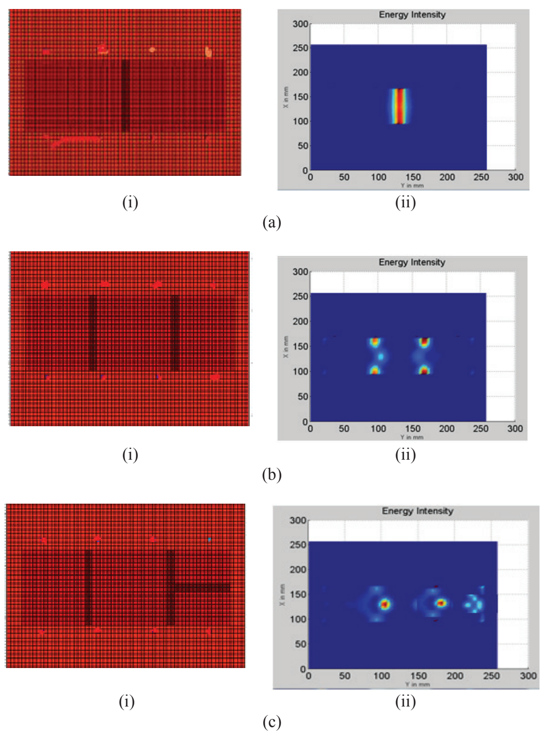


Figure 1: (i) FDTD model of the bricks and (ii) the corresponding images for (a) single crack through the brick, (b) unidirectional cracks and (c) multidirectional cracks.

The simulation results presented in Figure 1 indicate the maximum focusing corresponds to the high energy, which represents the crack location. Figure (a)i-ii show both the position and size of the single crack has been accurately mapped in the right place even though there some clutters around the reconstructed image. When the reconstructed and original images are compared together, it can be seen that the cracks have been properly mapped even though the shape of the reconstructed object appeared a little distorted. Notwithstanding, the DAS algorithm detected the crack and distinguished their sizes and positions.

Meanwhile, Figure (b)i-ii shows that both cracks were successfully recovered. Although, it is observed that the shape of the targets were distorted. However, most importantly is that the size and the location of the cracks seem to be accurate. It can also be noticed from the images in Figure 1(c)i-ii that the horizontal crack on the side has less focusing intensity compare to the cracks at the center. This may be due to the fact that more signal power are directed to the center of the brick as compared to other positions. In addition, the antennas on the opposite side tends to be far away from the object close to the two edge.

The variation and inaccuracy from the 2-D FDTD simulation results are limited since it can only scan in a single plane and not in multiple planes that gives information about the target in all directions. In order to validate the effect of scanning from multiple planes, an experiment with real bricks and antennas shall be conducted.

B. *Experimental Result*

The experimental result described in this section gives attention to the sensor ability, imaging quality and reconstruction method of DAS in detecting cracks from a brick material. The hardware configuration of the experimental work is summarized in Figure 2(a). A vector network analyzer (VNA) was used as transceiver. Pairwise pulse measurements from the multiple antennas were sequentially done through multiplexing. The measurements were carried out on a residential-grade concrete brick as shown in Figure 2(b). The close-view of the sensor is shown in Figure 2(c). As can be seen, the sensor is very compact with a length of less than 2 cm. By using multiple sensors in an array, the coverage area can be arbitrarily adjusted according to the structure under study.

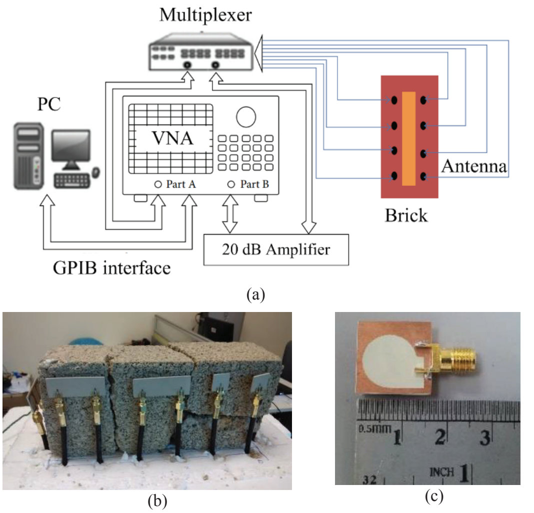


Figure 2: (a) Schematic diagram of the experimental setup, (b) mounting of the sensor array surrounding the brick and (c) the P-shaped Wide-slot antenna.

The first experiment was performed to validate the simulation in Figure 1(a). The brick is broken into two unequal halves with the crack created through it. The measurements were carried out with half of the sensors are on the same height at the upper part and the remaining half were placed at lower height separated by a distance of 40 mm so that they still remain in their far field. The homogeneous brick is measured in this case to act as the "background" for this brick and then the heterogeneous.

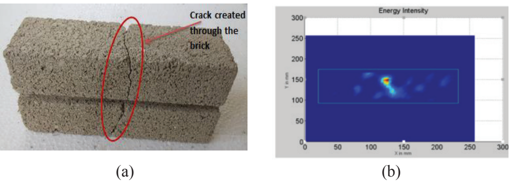
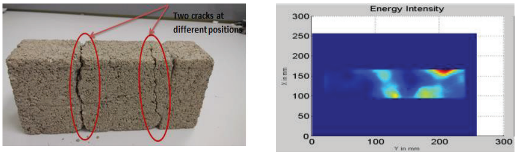


Figure 3: (a) A single crack cut through the brick and (b) the corresponding imaging results comparing the reconstruction of a single crack on the brick using UWB frequencies

From the experimental result in Figure 3(b), the single crack through the brick has been successfully detected by this proposed system. It can be observed that the maximum energy intensity was focused more at one point than others even though it was a crack and not a hole. From the theory, when two antennas are directly facing each other they tends to have maximum power and better signal reception than when they are at different angle. Therefore, for crack not to be detected as a single point there is need for better sensor arrangement.

The second experiment was conducted according to the model in Figure 1(b). This time, the brick consists of two cracks since it is possible to have more than just a crack on a single brick in most cases. The brick is broken into three pieces and joined together to create two different cracks at different position through the brick for the detection. The cracks created were of irregular shape and even the sizes are a little bit different since the brick were broken and not cut through. In addition, the approximate distance between the two cracks is less than $\lambda/14$. As a usual scenario for this algorithm, "background" information was first obtained which was then use in the algorithm for image reconstruction. The brick phantom used for this phase is displayed in Figure 4(a).

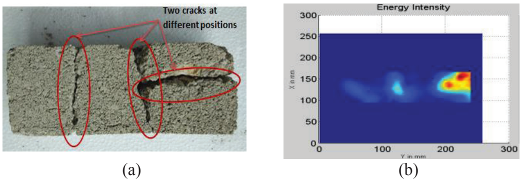


(a) (b)

Figure 4: (a) Two unidirectional cracks on a single brick and (b) the corresponding imaging results.

From the result presented in the Figure 4(b), the system is able to detect two cracks on a single brick, even though it can be seen that there is decrease in energy intensity of the reconstructed image at some points. Comparing the simulation result with the experiment indicates that the two agreed together.

The third experiment was performed to emulate the multidirectional crack model shown in Figure 1(c), where three cracks with one of the cracks presented in the horizontal form and the two other cracks in vertical form were present.

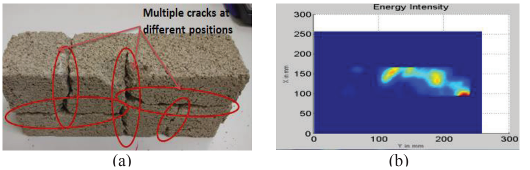


(a) (b)

Figure 5: (a) Three multidirectional cracks on a single brick and (b) the reconstructed imaging results.

Furthermore, it can be noticed that the maximum energy intensity was decreasing with the increase in the number of cracks. From the above Figure 5(b), the reconstructed image shows that there is a crack on the brick but the location, and sizes of the cracks were not properly detected. At one point, it shows more clutter other than the crack. Therefore, this system could not effectively detect the object size and position accurately as compared to single and two line cracks on a single brick.

During natural disaster like earth quake civil structure can be in terrible situation and may be hidden due to paints or other coverings. This part tends to see the sensor performance in term of a critical scenario where at least there are six cracks on a single brick. Due to this reason, the final experiment is performed with the brick broken into six pieces to create a multiple cracks of various styles on a single brick. However, with this number of crack on a single brick, the building must have been in a critical state or at the point of collapse but we desire to test the ability of our proposed sensor and the algorithm to detect such cracks that are densely close together. Before the brick were broken into several pieces, the background scanning was first carry out and after which the cracks were created. The imaging of the object was carry out after the cracks were scanned.



(a) (b)

Figure 6: (a) Multidirectional cracks on a single brick and (b) the reconstructed imaging results (critical state).

The above situation represents a critical situation; the brick consists of six cracks of different orientation and sizes. The system fails to detect both the size and the location of the cracks even though the reconstructed image shows that there is a problem with the brick. From the frequency range used and the value of λ as 75 mm, it can be notice that the distances between the objects are too close as compared to the calculated value. Therefore, the system may recognize it as a single crack. This maybe the reason why the all cracks are joined together as one.

IV. CONCLUSION

In conclusion, several models of different crack sizes, location and position have been simulated in order to study the performance and accuracy of DAS algorithm and the ability of this sensor to detect cracks from cement base materials. The results of the reconstructed images were compared with the actual crack position in FDTD. The cracks had been successfully localized, even though the shapes are distorted. Despite this shortcoming, high intensity regions in the reconstructed images appear to be correlated to the number of cracks. This feature can be manipulated to determine the severity of the crack condition inside a structure. Considering the efficiency of the DAS algorithm and the compactness of the sensors, microwave-imaging technique can be an effective tool for detecting single and multidirectional cracks.

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