Microwave Tomography Technique for Concrete Diagnosis

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Abstract— "Successive Estimation Technique" is introduced to microwave tomography in concrete diagnosis. It adjusts target area automaticly according to the measurement of scattering wave, target range of scattering analysis and the material electromagnetic property of concrete body, and reconstructs tomography image (a distribution of permittivity, conductivity or magnetic permeability) rationally and effectively.

1. INTRODUCTION

Concrete is a very fantastic construction material and concrete buildings occupy over than 30% of whole buildings of office, hotel, and facilities for education and employee welfare. However, concrete can be affected by fire, aggregate expansion, sea water effects, bacterial corrosion, calcium leaching, physical and chemical damage, and many incidents, such as falling concrete, happen all over the world. Because some of degradation could also occur unseen in concrete, techniques for concrete diagnosis are needed in construction industry. Radiography is one of well-known non-destructive inspection techniques with very high precision, but human health risk is involved and the applicable location is limited. On the other hand, Ground Penetrating Radar is developed for concrete diagnosis [1, 2]. The device radiates electromagnetic waves to a concrete body and receives the waves scattered by the surface of the body as well as reinforcing steel bars, cavities, or other objects in the body. However, in practice it is sometimes difficult to comprehend and interpret the scattering waveforms shown on the screen of the device directly.

Microwave tomography is a hopeful technique for concrete diagnosis [3–5]. The distributions of permittivity ε, magnetic permeability μ and conductivity σ of a concrete body are computer-reconstructed by making use of the measurement of scattering waves.

Let us consider an inverse scattering problem shown in Figure 1. A microwave is illuminated from a transmitter to a concrete body, and is measured by a receiver located at the same location as the transmitter. To reconstruct the distributions of material parameters ε, μ and σ, it is assumed that the concrete body is consist of many small cubes (cells), and ε, μ and σ are uniform in each cube. A cost-function is introduced as

$$Cost(\boldsymbol{\varepsilon},\boldsymbol{\mu},\boldsymbol{\sigma}) = \frac{\int_{t^{\text{begin}}}^{t^{\text{end}}} \|E^{\text{measured}} - E^{\text{estimated}}(\boldsymbol{\varepsilon},\boldsymbol{\mu},\boldsymbol{\sigma})\|\mathrm{d}t}{\int_{t^{\text{begin}}}^{t^{\text{end}}} \|E^{\text{measured}}\|\mathrm{d}t}, \tag{1}$$

where

$$\boldsymbol{\varepsilon} = (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_N), \quad \boldsymbol{\mu} = (\mu_1, \mu_2, \ldots, \mu_N), \quad \boldsymbol{\sigma} = (\sigma_1, \sigma_2, \ldots, \sigma_N),$$

ε_i, μ_i and σ_i ($i = 1, 2, \ldots, N$) are material parameters of i-th cube, E^{measured} is the wave measured with the receiver from time t^{begin} to t^{end}, and $E^{\text{estimated}}$ is the wave estimated with wave scattering analysis technique, such as Finite-difference time-domain (FDTD) method. Then $\boldsymbol{\varepsilon}$, $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$ are estimated by minimizing the $Cost$.

Unlike common case of inverse scattering problems, usually a target of concrete diagnosis cannot be separated from the concrete structure body and taken into a radio wave darkroom for measuring.

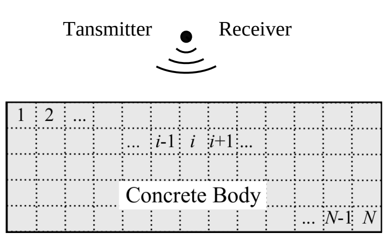

Figure 1: Tansmitter, receiver and concrete body.

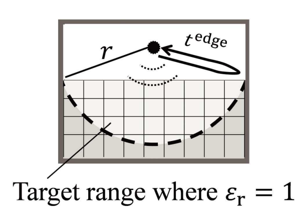

Figure 2: Simulation range and target zone.

Because computer simulation of wave scattering has to be limited in a finite range (simulation range), the time t^{end} must be less than t^{edge}, the time that a scattering wave from edge of the simulation range arrives at the receiver, refer to Figure 2. Therefore the simulation range can be divided into two parts. One is called "target zone" in which the wave scattered by any cube is measured by receiver from t^{begin} to t^{end} ($t^{\text{end}} < t^{\text{edge}}$), and the other one is "non-target zone" in which wave scattered by any cube cannot arrive at the receiver during that time. For example, the target zone becomes a circular region with radius r shown with dashed line in Figure 2, if all the cubes are free space (relative permittivity $\varepsilon_r = 1$).

Obviously, only the material parameters of those cubes in the target zone are reconstructible with the cost function (1). If one estimates the material parameters of all cubes in simulation range by minimizing (1), the reconstruction results for the cubes in non-target zone will be not valid. Therefore, it is important to make sure the target and non-target zones. But in a concrete diagnosis we cannot find out the target zone in advance, because material parameters of all cubes (the concrete body) are unknown. It is one of the key problems of microwave tomography in concrete diagnosis.

2. SUCCESSIVE ESTIMATION TECHNIQUE

Successive Estimation Technique is an algorithm to reconstruct material parameters of cubes step by step.

First let us consider reconstructing material parameters of one cube in front of the transmitter(receiver) illustrated in Figure 3, which is our primary target this time. We set t^{begin} and t^{end} to the time that waves scattered by the front and back surface of the cube arrive at the receiver, where the cube is assumed as free space for the present. At the same time, other cubes from which the scattering waves may arrive at the receiver during $t^{\text{begin}} \sim t^{\text{end}}$ are regarded as secondary targets. The cubes of primary and secondary targets compose the target zone of (1) from t^{begin} to t^{end}. Just the material parameters of the primary and secondary targets are objects of the minimization, so that the number of variables is small and the minimization becomes easy to do.

It is noted that precision of the reconstruction for secondary targets may fall in some cases, because the information of scattering waves E^{measured} during the time $t^{\text{begin}} \sim t^{\text{end}}$ may be not enough for reconstructing secondary targets. However, a good reconstruction of the primary target is enough for us. We can scan a concrete surface by using a device like "handy-search" shown in Figure 4. Then the material parameters of the cubes in the first layer (surface layer) can be obtained one by one with the method.

Next let us focus on reconstructing of the cubes in the second layer. The reconstructed material parameters of primary targets in the first layer will be used as known quantities. The wave propaga-

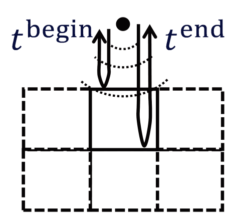

Figure 3: Time for reconstructing primary target (the cube in front of transmitter).

Figure 4: Scan a concrete surface with a handy-search device.

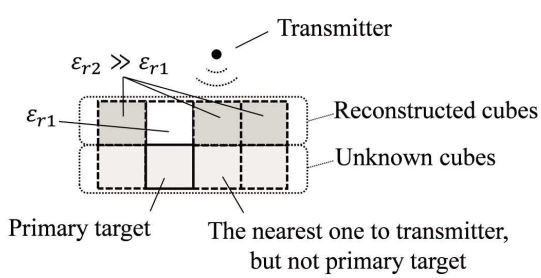

Figure 5: The cube at which the incident wave arrives first is selected as "primary target".

tion path may become complicated in this case, because multiple scattering phenomenon may occur between different cubes. We redefine "primary target" for each transmitter position as the cube at which the incident wave arrives first. Even if a cube is the nearest one to a transmitter, it is not necessarily a "primary target" of the transmitter, as showed in Figure 5. To find out the primary target for each transmitter position, we use a pulse wave and a wave propagation simulation tool, such as a FDTD simulator, to observe the time that wave peak arrives at center of a cube, where all unknown cubes are assumed to be free space. According to the time that the incident wave arrives at the center of the primary target and pulse width of the incident wave, t^{begin} and t^{end} for primary target can be estimated and thereupon secondary targets are determined. Finally, material parameters of primary and secondary targets are estimated by minimizing the cost function.

The cubes in other layers are reconstructed by repeating previous steps. With the target layer getting deeper, the number of secondary targets becomes more and more. An effective means is to estimate the targets of all the transmitter positions in one time. In that case, cost function for M transmitter positions is defined as

$$Cost\left(\boldsymbol{\varepsilon}^{\text{targets}}, \boldsymbol{\mu}^{\text{targets}}, \boldsymbol{\sigma}^{\text{targets}}\right) = \sum_{m=1}^{M} \frac{\int_{t_m^{\text{begin}}}^{t_m^{\text{end}}} \left\| E_m^{\text{measured}} - E_m^{\text{estimated}}(\boldsymbol{\varepsilon}_m, \boldsymbol{\mu}_m, \boldsymbol{\sigma}_m) \right\| \mathrm{d}t}{\int_{t_m^{\text{begin}}}^{t_m^{\text{end}}} \left\| E_m^{\text{measured}} \right\| \mathrm{d}t}, \tag{2}$$

where E_m^{measured} is wave measured by receiver at position m from time t_m^{begin} to t_m^{end}, $\boldsymbol{\varepsilon}_m$, $\boldsymbol{\mu}_m$, $\boldsymbol{\sigma}_m$ are vectors of material parameters of primary and secondary targets for transmitter at position m, and $\boldsymbol{\varepsilon}^{\text{targets}}, \boldsymbol{\mu}^{\text{targets}}$, $\boldsymbol{\sigma}^{\text{targets}}$ are the sum of sets $\boldsymbol{\varepsilon}_1 \sim \boldsymbol{\varepsilon}_M$, $\boldsymbol{\mu}_1 \sim \boldsymbol{\mu}_M$, $\boldsymbol{\sigma}_1 \sim \boldsymbol{\sigma}_M$, respectively. It is noted that a secondary target for a transmitter position may be a primary target for another transmitter position, and t_m^{end} must be less than t_m^{edge}, the time that a scattering wave from edge arrives at receiver located at position m.

The procedure of successive estimation is summarized below.

1. Scan concrete surface, and measure scattering waves at M positions.
2. Make sure the minimum time that scattering waves from edges of simulation range for each position t_m^{edge}, $m = 1, 2, \ldots, M$.
3. Determine primary and secondary targets for each transmitter position, as well as the period of time $t_m^{\text{begin}} \sim t_m^{\text{end}}$ during which the measurement of scattering waves E_m^{measured} will be used for reconstructing material parameters of the targets. However, the data of scattering waves measured at position m as well as the targets for the position will be discarded if t_m^{end} is larger than t_m^{edge}. If all the measurements are discarded, stop the procedure.
4. Reconstruct material parameters of the targets by minimizing the cost function (2). Material parameters of primary targets obtained in the minimization will be used as known quantities in next step, and those of secondary targets will be discarded.
5. Go to step 3 if there are any unknown cubes need to reconstruct.

3. NUMERICAL EXAMPLES

First let us have a simple 2-D example of reconstructing a uniform body where $\varepsilon_r = 9$, and other material parameters are the same as free space, as shown in Figure 6. A raised cosine pulse

$$P(t) = \begin{cases} \left[1 - \cos\left(\dfrac{2\pi}{T} t\right)\right]^2 & (0 \le t \le T) \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

is used as wave source. Simulation range is meshed into 31×5 square cells, where the cell width w_c is set to half of the pulse width. Waves are measured by a transmitter and a receiver located $2w_c$ away from the surface at 23 positions. A FDTD simulator is employed to simulate wave propagation and scattering, and conjugate gradient method is employed to minimize the cost function (2). Searching space of relative permittivity is from 1 to 20.

A reconstructed result is shown in Figure 7. According to the procedure of successive estimation, we had 23 primary targets (cells) for the first iteration, 17 and 11 primary targets for the 2nd and 3rd iteration, and finally, just 1 primary target for the 4th iteration. It is noted that successive estimation technique just reconstructs the cubes in the target zone of the simulation range.

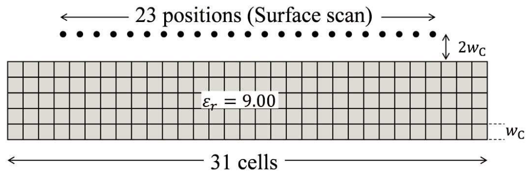

Figure 6: Model setting of example 1.

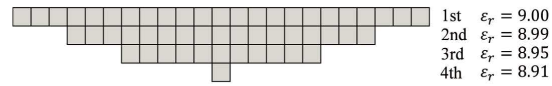

Figure 7: Reconstruction result of example 1.

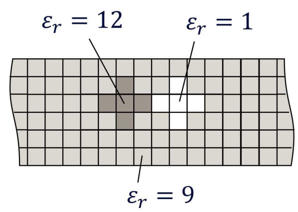

Figure 8: Model setting of example 2.

9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
8.99	8.96	12.01	8.99	9.00	1.00	9.00	8.99
8.94	11.96	12.06	12.03	1.00	1.01	1.00	9.10
8.91	9.14	12.46	8.98	9.07	1.01	9.08	9.32
8.86	9.17	9.29	9.00	9.01	8.98	9.00	9.33

Figure 9: A part of reconstruction result of example 2.

Next let us have a little more complex example. The model is based on example 1, but one "aggregate" ($\varepsilon_r = 12$) and one "hollow" ($\varepsilon_r = 1$) are inserted in, as shown in Figure 8. Of course, to reconstruct a wider deep region we need a wider simulation range. A part of reconstruction result of example 2 is given in Figure 9.

4. CONCLUSIONS

Successive estimation technique is an iteration method to reconstruct target body part by part, by using time-divided information of the scattered wave. It is suitable for microwave tomography in concrete diagnosis. High accuracy tomography images are obtained efficiently in numerical experiments.

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