Electromagnetic Array Imaging of Steel Bars in Concrete Using High-Speed SAFT

Daiki KISHIOKA 1, Taishi MATSUMOTO 1, Kazuyuki NAKAHATA 1
1 Department of Civil and Environmental Engineering, Ehime University, Ehime, Japan.
Phone: +81-89-927-9812, Fax +81-89-927-9840; e-mail: kishioka.daiki.11@cee.ehime-u.ac.jp, nakahata@cee.ehime-u.ac.jp

Abstract
The electromagnetic radar method is widely used to detect steel bars in concrete materials as a non-destructive testing tool. This study proposes a three dimensional imaging method using array antennae, which makes use of scattered electromagnetic waves, measured by every two-antenna combinations as a transmitter and a receiver, to synthesize high amplitude beams for any points in an inspection area. By combining the beam-forming technique with the synthetic aperture focusing technique (SAFT), we can offer a high-resolution image of steel bars. Our method is accelerated with massively parallel calculation with graphics processing units. In this study, we develop a new antennae for a matrix array arrangement, and investigate the performance with experimental measurement. Here we demonstrate the reconstruction of steel bars in concrete material using the accelerated SAFT.

Keywords: Imaging of steel bars, electromagnetic wave, synthetic aperture focusing technique (SAFT), matrix array antenna, simulation

1. Introduction
The electromagnetic radar is a nondestructive method that uses pulses to image the subsurface area. For the nondestructive testing in concrete, some commercial hardware, which radiate electromagnetic wave in the microwave band and receive the reflected signals from subsurface structures, are used. Conventional methods use pulse-echo signals from steel bars, and output images based on the magnitude of the reflected signals, i.e., B-mode images. In the field of ultrasonic testing, a post-processing beam-forming technique has been proposed that utilizes a complete set of signals of all combinations of transmission and reception elements. This approach is referred to as either full matrix capture (FMC) [1] or sampling phased array [2]. In FMC, each array element is sequentially used as an emitter and all other array elements with number \( N \) are used as receivers. By changing the emitting element, we obtain a set of \( N \times N \) signals that is used to form the beam. The combination of all signals enables the generation of focal beams at any point in the region of interest. Here, the beam-forming approach based on post-processing imaging technique is introduced in the electromagnetic radar imaging. By combining the beam-forming technique with the synthetic aperture focusing technique [3] (SAFT), it is expected that we enhance the resolution of the image of steel bars. The calculation processes of the beam-forming and SAFT are accelerated with massively parallel calculation with graphics processing units (GPUs). The GPU computation is possible with a programming tool with the Compute Unified Device Architecture (CUDA) by NVIDIA Corp.

In this study, we consider three dimensional (3D) imaging of steel bars in concrete using the high speed SAFT. For the 3D imaging, the antenna needs to be arrayed in a matrix form over the target concrete. Here, we develop a new antenna which has a conductor of a log-spiral pattern on a dielectric substrate. Although the antenna is omnidirectional, it can transmit electromagnetic wave with a large amplitude. The performance of the imaging method is investigated by
experimental measurements using a concrete specimen. The method is also verified through a numerical simulation obtained by the 3D electromagnetic finite integration technique [4] (EMFIT) code.

\section{FMC and SAFT}

Consider an antenna arrayed in a matrix form as shown in Fig. 1(a). Each antenna is successively used as the transmitter, while all other antennae are used as receivers. The transmitting wave is emitted by the \( i \)-th antenna, and the scattered waves are received at all antennae individually. The received signal at the \( j \)-th antenna is stored in a signal matrix \( M_{ij} \). The number of signal samples in each transmission and reception combination is \( N_t \), and the signal samples are recorded in a signal matrix that contains all the acquired \( N \times N \) combinations (Fig. 1(b)). Using the dataset in the signal matrix, a focal beam at an arbitrary point can be generated. This approach is referred to as the FMC \([1]\). The position \( x[k, l, m] \) represents the target voxel where the focal beam is being generated. The flight time \( T_{klm}^\omega \) of the electromagnetic wave between the target voxel \( x \) and the center of the array \( x^o \) is described as follows:

\begin{equation}
T_{klm}^\omega = \frac{2|x - x^o|}{c}
\end{equation}

where \( c \) is the electromagnetic wave velocity in the material. The flight time from the \( i \)-th to \( j \)-th element via \( x \) can be expressed as \( T_{klm}^\omega - \Delta t_{klm}^{ij} \). To obtain the focal beam, we stack the signal data by considering the delay \( \Delta t_{klm}^{ij} \) as follows:

\begin{equation}
F(x[k, l, m], t) = \sum_{i=1}^{N} \sum_{j=1}^{N} M_{ij}(t - \Delta t_{klm}^{ij}), \quad (k, l, m) = (1 \cdots K, 1 \cdots L, 1 \cdots M)
\end{equation}
In Eq. (2), \( K, L, \) and \( M \) are the voxel numbers in the \( x_1, x_2, \) and \( x_3 \) directions, respectively. After the beam forming, we determine the amplitude \( R \) at the flight time \( T_{klm}^0 \) as follows:

\[
R(x) = F(x[k, l, m], T_{klm}^0)
\]  (3)

Using Eqs.(2) and (3), the imaging procedure allows a complete scan with a fine pitch in a target area. The delay-and-sum approach based on post-processing imaging technique is referred to as the SAFT. If there is a steel bar at \( x \), the amplitude \( R \) will be high. A color map of \( R \) is output on the PC monitor.

3. SAFT Simulation using EMFIT

For the verification of imaging algorithms, we perform the SAFT simulation using the EMFIT. The EMFIT is a grid-based spatial discretization method that works in conjunction with a leap-frog time-marching scheme. The EMFIT codes was optimized for parallel computation using the OpenMP and MPI, and the performance of the developed code was investigated using a cluster system at Kyoto University [5]. As shown in Fig. 2, the EMFIT simulation comprises the FMC experiment for \( N = 64 \) (8 \( \times \) 8) antenna positions and a 3D grid of 440 \( \times \) 940 \( \times \) 140 cells which corresponds to a concrete sample size of 440 \( \times \) 940 \( \times \) 140mm. The model is surrounded by the perfectly absorbing layer with 30 mm width. The diameter of the steel bar is 22 mm, and they are located at a depth of 90mm from the top surface of the model. The material parameters are the electrical permittivity \( \varepsilon = 57.00 \times 10^{-12} \) F/m, the magnetic permeability \( \mu = 1.257 \times 10^{-6} \) H/m, and the electric conductivity \( \sigma = 0.001 \) S/m for concrete; and \( \varepsilon = 8.85 \times 10^{-12} \) F/m, \( \mu = 1.257 \times 10^{-6} \) H/m, and \( \sigma = 0.0 \) S/m for air. The steel bars are modeled as conductors. In the simulation, an electromagnetic pulse wave of center frequency 4.0 GHz is emitted from an antenna area of 40 \( \times \) 40 mm. The pulse wave is generated by varying the electric current with the same phase inside the antenna. The computations were performed on a supercomputer system at Kyoto University, Japan.

Fig. 2: Numerical model of concrete with a steel bar. Array antennae with \( N = 64 \) are arranged over the model (Lift off is 2 mm)
Fig. 3: (a) 3D image of steel bar (iso-surface volume rendering, $R = 0.5$). Image of cross section in $x_1 - x_3$ (b) and $x_1 - x_2$ (c).

The imaging results by the SAFT simulation are shown in Fig. 3. Figure 3 (a) shows the isosurface volume rendering at the threshold $R = 0.5$. From Fig. 3 (b), the depth and location of the steel can be evaluated accurately. However, it is difficult to reconstruct the shape of steel near vertical walls (Fig. 3 (c)). As a reason for this, it was mentioned that we could not receive the significant wave from the steel near the wall because the electromagnetic wave reflected at the steel to the far side. The time for the SAFT calculation was approximately 0.8 sec by a lap-top with a GPU (Geforce GTX880M).

4. Characteristics of the log-spiral antenna

In this study, we develop a new antenna which has a conductor of a log-spiral pattern on a dielectric substrate. The performance of the log-spiral antenna is investigated by comparing with a conventional antenna (bow-tie antenna) which is mounted in an electromagnetic radar unit (Japan Radio, NJJ-105). The pictures of the bow-tie and log-spiral antennae are shown in Fig. 4. The bow-tie antenna has two circular conductors on the dielectric substrate as shown in Fig. 4). Since the beam from the antenna is linearly polarized, the electromagnetic wave is radiated with strong directivity to the area below the antenna. On the other hand, the spiral antenna has a conductor of copper foil in a spiral alignment, and radiates circular polarized electromagnetic wave. Because of this polarization, the electromagnetic wave propagates in wide angle from the antenna section. Reflected signals from a steel plate with the log-spiral and log-spiral antennae are shown in Fig. 5. From Fig. 5, it is found that the dominant frequency with the log-spiral antenna is shifted to the higher side than the one with bow-tie antenna. Furthermore, the signal amplitude by the log-spiral antenna increases than bow-tie antenna.

Next, the directivity of the log-spiral antenna is investigated by using pitch-catch signals obtained when the antennae are facing each other as shown in Fig. 6. In Fig. 6 (a), the receiving antenna is placed facing to the transmitting antenna at the same rotation angle (Pattern A). On
Fig. 4: Pictures of the bow-tie antenna (a) and log-spiral antenna (b)

Fig. 5: Reflected waveform and its Fourier spectrum obtained by (a) bow-tie antenna and (b) log-spiral antenna

the other hand, the receiving antenna is rotated 90 degrees from the transmitting antenna (Pattern B). The pitch-catch signals with bow-tie and log-spiral antennae are shown in Fig. 6 (b) and (c), respectively. It is found that the signal with the log-spiral antenna shows small change of the amplitude when rotating the receiving antenna. From the result, the log-spiral antenna shows the omnidirectional radiation property.

5. Imaging of the steel bar using log-spiral antenna

A concrete specimen with steel bars as shown in Fig. 7 were used for the validation of imaging. The diameter of the steel bar is all 38.1 mm, and steel bars are located in a reticular pattern. The shallowest bar is 100 mm deep, and the lower bar is 138.1 mm deep. We consider 11
locations for the antenna position, and place two antennae on a line over the specimen as shown in Fig. 7. We here switched the combination of transmission and reception by hand, and record the scattered signals in the signal matrix. In this study, we perform the imaging in the cross-sectional of $x_2-x_3$ plane whose region is $600 \times 300$ mm (pixel size is 1 mm) The sampling rate was 64 GHz. Therefore, we set $K = 600$, $M = 300$, and $N_t = 512$. For the sake of comparison, the imaging result with the bow-tie antenna is also shown. The bow-tie antennae are set at 15 locations, and moved changing the combination of transmission and reception. Figures 8 (a) and (b) show the imaging results with the bow-tie and log-spiral antennae, respectively. Here, $R$ was normalized by the maximum value in the imaging area. Both results in Figs. 8 (a) and (b) can reconstruct the shallowest steel bars clearly. However it is found that the shape of the lower steel bar is not clear. Since the polarization of the electromagnetic wave radiated by the bow-tie antenna is along the $x_1$ direction, it is difficult to detect the perpendicularly aligned steel bar to the polarization of the electromagnetic wave. On the other hand, the log-spiral antenna yields a good performance for three-dimensionally aligned steel bars. The time for the SAFT calculation was approximately 0.3 sec by a lap-top with a GPU (Geforce GTX880M).

6. Conclusions

In this study, we proposed a 3D imaging method of steel bars in concrete using matrix array antennae. Here we utilized the FMC method, in which electromagnetic waves were measured
Fig. 7: The concrete specimen and three dimensional arrangement of the steel bars.

Fig. 8: Imaging results of the steel bars with (a) bow-tie antenna and (b) log-spiral antenna
by every two-antenna combination as a transmitter and a receiver, to synthesize high amplitude beams for any points in an inspection area. The imaging process incorporated the FMC and SAFT can offer the high-resolution image of multiple steel bars. The SAFT simulation using the EMFIT modeling showed an accurate and clear image of steel bars. Furthermore the imaging method based on the FMC and SAFT was checked by the experimental measurement. In this study, we develop log-spiral antennae for a matrix array arrangement, and investigate the performance with experimental measurement. Since the log-spiral antenna radiates the electromagnetic wave omnidirectionally, three-dimensionally aligned steel bars can be reconstructed well. As a future work, we develop the 3D imaging system using the matrix array antenna and high-speed SAFT.

Acknowledgement

A part of this research work was performed with the supercomputer of ACCMS, Kyoto University.

References


