Locating embedded iron bars for wireless power transmission through reinforced-concrete wall

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Abstract

We previously showed that using low-frequency magnetic waves is effective for wireless power transmission (WPT) through reinforced-concrete walls. When a magnetic wave below 400 Hz was used, it was confirmed that the temperature increase of iron objects inside concrete is very small by numerical calculation based on a non-steady heat conduction equation that included a one-dimensional heat conduction term and heat generation term. However, even if the frequency was lowered to 60 Hz, the power loss was still serious due to magnetic coupling impedance caused by iron bars, such as a rebar lattice, inside the concrete wall. This fact was confirmed from both experiments and numerical calculations. In this study, we propose an iron bar location system using a pair of patch antennas to detect iron bars embedded in the concrete and use this information to place WPT couplers away from embedded iron. Then, we show that the proposed system can be adapted to concrete walls up to 70 cm thick by numerical calculation with the finite-difference time-domain method. Our research results will contribute to WPT in cases where iron bars or pipes are present inside a wall.

Keywords Wireless power transmission · Reinforced concrete · Non-destructive diagnostics · FDTD method

1 Introduction

We have started development of a method for charging the batteries of robots operating in structures that humans cannot enter, such as areas contaminated by radioactivity from the Fukushima nuclear disaster. Radioactively contaminated space is completely shielded by thick reinforced concrete walls. Thus, the charging of robots working in the interior is a very challenging research theme. We have proposed a magnetic resonance type wireless power transmission (WPT) using a low frequency, below 400 Hz [1]. Because electric power absorbed by any metal existing in the transmission space is proportional to the square of frequency, if the frequency is reduced to 60 Hz from 85 kHz, the power loss generated in the metal is reduced by a factor of 2,000,000. However, in the case of iron bars

arranged at regular intervals, the power loss was serious, even when the frequency is reduced to 60 Hz, as this paper explains quantitatively.

We think that if we can identify the arrangement of iron bars inside a concrete wall and arrange WPT couplers to avoid these bars, the power loss can be reduced. Non-destructive methods for inspecting the inside of concrete structures include the impact-echo method [2, 3], reinforced-concrete (RC) radar [4, 5], and X-ray transmission [6, 7]. Among them, RC radar is most frequently used, but the radio-wave intensity is restricted by radio regulation in Japan, and thus the exploration depth of RC rebar is up to 30 cm [8]. Because the dielectric constant of concrete increases with increasing moisture content, the depth limit will be shallower for a wall containing moisture [9]. For general RC radar, the position of an iron bar is estimated by

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measuring the amount of time it takes for the microwave radiated from a radar gun to be reflected by the bar and return to the radar; that is, all RC radars are the reflective type. A transmission type system is expected to be able to measure thicker walls because strong radio waves that are forward scattered would be measured; however, such a measurement method has not been proposed until now.

In this study, we calculated the temperature rise of an iron object placed in the transmission space for WPT using a non-steady heat conduction equation that includes a one-dimensional heat conduction term and heat generation term. Then, we investigated power loss of WPT in a RC wall in an experiment using a small-scale WPT system and concrete wall and numerical calculations by the finite-difference time-domain (FDTD) method [10, 11]. Based on these results, we propose a transmission type iron locating method using one pair of patch antennas. Then, by FDTD simulation, we investigated how penetrated wave intensity changes with iron bar diameter and burial depth, and we showed that our proposed method can be adapted to concrete walls over 50 cm thick.

2 Influence of iron object on WPT

First, the temperature of iron buried in concrete is discussed in this section. It is difficult to measure the surface temperature of an iron bar buried in concrete. Thus, the temporal change of temperature in an iron object set in the power transmission space was estimated using one-dimensional non-steady heat conduction with heat generation. The analysis model is shown in Fig. 1. An iron plate (with thickness d of 1.0 mm) was sandwiched by two concrete blocks, each 50 mm thick. The amplitude of magnetic flux density (B) was assumed to be 0.2 T. The electric power loss per unit of volume generated in an iron object can be identified by Eq. (1).

$$Q = \frac{\pi^2}{6\rho_e} B^2 f^2 d^2, \quad (1)$$

where ρ_e is electric resistivity of iron. The basic equation for identifying the surface temperature of iron is given by Eq. (2), which is non-steady heat conduction equation constructed with the one-dimensional heat conduction term and a heat generation term.

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} + \frac{Q}{\rho c}, \quad (2)$$

where a is thermal diffusivity, λ is thermal conductivity, ρ is density, and c is specific heat. The basic equation was discretized by the Crank-Nicolson method. Equation (3) was

Fig. 1 Analytical model for temperature in iron plate sandwiched by two concrete blocks

used for identifying the temporal change of temperature [12].

$$T_i^{n+1} = \left\{ \frac{a}{2} \left(\frac{T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1}}{\Delta x^2} + \frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{\Delta x^2} \right) + \frac{Q}{\rho c} \right\} \Delta t + T_i^n, \quad (3)$$

where a is defined as the ratio of thermal conductivity and the product of density and specific heat [$\lambda/(\rho c)$], i is the number of discrete points in the spatial coordinate, and n is the number of discrete points in the time coordinate. The heat generated in the iron plate was transferred to concrete by heat conduction. The temperature was assumed to have a uniform distribution in both the surface and depth directions. The temperature of the concrete surface was given as constant at 20 °C as a boundary condition. The discrete interval on the spatial coordinate, Δx , was given as 0.1 mm in iron and 0.5 mm in concrete. The discrete interval on the time coordinate, Δt , was 10 s. The initial temperature T_0 was given as 20 °C, and the temperature after heat generation was analyzed. Figure 2 shows the analytical results for various frequencies of wireless transmission. At $f=85$ kHz, which is widely used for WPT for electric vehicles, is saturated at about 300 °C. When the frequency was reduced to 43 kHz, the saturated temperature was still too large at 93 °C. However, the saturated temperature was only slightly increased from the initial temperature (20 °C) when using a transmission frequency of 400 Hz, which produced a temperature increase of 6.5×10^{-3} °C.

Using a low transmission frequency is one useful method for reducing the temperature increase in iron objects.

Fig. 2 Temporal temperature change of iron plate: **a** results for frequencies of 60 Hz, 400 Hz, 43 kHz, 85 kHz, and 104 kHz; **b** results for 60 Hz and 400 Hz (dashed square in in lower right corner of **a**). Thermal conductivity λ_1 of 80.3 W/(m K), density ρ_1 of 7870 kg/m³, and specific heat c_1 of 442 J/(kg K) were used in the iron plate [13]. Thermal conductivity λ_2 of 1.2 W/(m K), density ρ_2 of 2400 kg/m³, and specific heat c_2 of 900 J/(kg K) were used in the concrete block [13]

Figure 3 is a picture of the trial coupler device with a driving frequency of 60 Hz. The details of this device are described in Ref. [14]. This miniature model was used for experiment

to avoid the difficulty of building a thick concrete wall. Two types of concrete wall were prepared, one with internal iron bars and the other without iron bars. For the concrete wall without an iron bars, the transmission efficiency was 78% and transmission power was 850 W. In contrast, for the concrete wall with iron bars, the transmission efficiency and power were 67% and 717 W, respectively. The power reduction of 11% was not only caused by eddy-current loss. We thought that the large power loss was also caused by the two couplers, and not only the iron lattice. Thus, electromagnetic numerical simulation by the FDTD method was performed for the couplers shown in Fig. 3. The details of the FDTD methodology are described in Ref. [15]. In Fig. 4, two-dimensional magnetic flux distributions were constructed by time-average over 0.25 periods of magnetic wave. Figure 4a shows that there was nothing in the transmission space. From this result, the estimated value of coupling coefficient (k) was 0.234. We already confirmed that this value was similar to experimental result. Figure 4b shows the result for a 10 cm-thick concrete wall without iron bars. Here, the physical properties of concrete were used. The conductivity σ was 0.034 S/m, relative permittivity ϵ_r was 9.0, and relative magnetic permeability μ_r was 1.0. The estimated k value in this case was 0.237. Figure 4c shows the simulation result, in which iron bars in a concrete block were arranged at intervals of 15 cm. Figure 4d shows the simulation result for iron bars arranged at intervals of 7.5 cm. When there are iron bars in the transmission space, the k value decreased, which was caused by obstruction from the interlinked magnetic flux between the feeding and receiving couplers. In this simulation result, the k value in the case of Fig. 4c was 0.178, and in the case of Fig. 4d was 0.163. Equation 4 represents the efficiency of the WPT system [16].

$$\eta = \frac{1}{1 + \frac{2}{k\sqrt{Q_1Q_2}} + \frac{2r_c(k+k^{-1}-1)}{r_2Q_2}}, \quad (4)$$

Fig. 3 Scale model for the experiments: **a** from the front, **b** from the side. The concrete is 10 cm thick, the diameter of iron bars is 5 cm, and the lattice has bar intervals of 15 cm. The iron lattice was buried 5 cm deep from the wall surface

Fig. 4 Simulation results of magnetic flux density distribution: **a** without wall, **b** 10-cm-thick concrete wall without iron bars, **c** reinforced concrete with 5-mm-diameter iron bars arranged at intervals of 15 cm, **d** reinforced concrete with 5-mm-diameter iron bars arranged at intervals of 7.5 cm

Fig. 5 Relationship between k value and copper and core losses

where r_2 is the secondary winding resistance, r_c is the core loss resistance, and Q_1 and Q_2 are the respective quality factors of the primary and secondary coils. The first term in denominator has relationship to copper loss, and the second term has relationship to core loss. In this equation, the eddy current loss is not included. The process of deriving Eq. (4) was shown in Ref. [16]. From this equation, it is clearly that the loss generating in WPT couplers (copper loss and core loss) is increased with reduced k value. The parameters for calculation were used test device in Fig. 3. Figure 5 shows the relationship between k value and copper and core losses. The both of copper loss and core loss were increased with reduced k value. For example, when k value was reducing to 0.178 from 0.234, total loss was increased by 6.3% in order to increase with copper loss and core loss. In addition, the total observed loss increased by 11% due to eddy current losses in the iron lattice.

3 Iron bar locating system

From the results of Section II, even if the frequency is lowered, it was found that it is better to place WPT couplers so as to avoid iron bars. However, detailed drawings about placement of iron bars generally are not available for existing walls, so it will be necessary to detect them. Figure 6 is a schematic drawing of the iron bar locating system that we are proposing. This method uses one pair of patch antennas, as shown in Fig. 7a; these patch antennas have directivity, as shown in Fig. 7b. Searching for iron bars is performed while simultaneously moving both antennas in the horizontal (x) direction. A transmitting (T_x) antenna continuously emits microwaves, and the penetrated wave is detected at a receiving antenna (R_x) to specify a position in the x direction where an iron bar is buried. Since

Fig. 6 Schematic drawing of iron bar locating system using micro-waves

the patch antenna can slide the antenna surface across the surface close to the concrete, the patch antenna has a structural advantage. A dipole antenna can be considered as another candidate, but it is unsuitable for this application because it radiates radio-waves backwards.

The reinforced concrete block used in the FDTD simulation was a rectangular parallelepiped (length: 50 cm, width: 100 cm, height: 140 cm), as shown in Fig. 6, and we assumed that the relative permittivity ϵ_r and conductivity σ of concrete were uniform and isotropic. Conductivity of concrete was estimated by experiment as $\sigma = 0.034$ S/m. For the relative permittivity of concrete, we used a representative value of $\epsilon_r = 9.0$ for concrete with average moisture content. Setting such medium constants produced a propagation decay rate of about 40 dB/m, which is almost the same as our experimental results (40–50 dB/m).

The cylindrical iron bars to be detected were buried in the concrete block. In Fig. 6, although only one iron bar is illustrated, numerical calculation was also performed for two parallel iron bars. In this simulation, since iron bars with diameters of 20–64 mm were assumed, a microwave

Fig. 7 a Photograph and schematic drawing of patch antennas, b directional pattern of patch antenna

of 1.2–4.8 GHz was used, in which the wavelength of microwave in the concrete was about same as the diameter of iron bars.

Figure 8 is a coordinate system and an arrangement of the antennas and an iron bar when viewed from above the model shown in Fig. 6. An alternating current of $J_0 \cos \omega t$ was given to T_x antenna with a width of $d_w = 41$ mm. Here, J_0 is the maximum value of the current, and ω is the angular frequency. We assumed that this current flows uniformly in the section of the width d_w ($x - d_w/2 \leq x \leq x + d_w/2$) in the x direction. A magnetic wave having an electric field in the z direction was transmitted to the inside of the concrete

Fig. 8 Coordinate system of two-dimensional analysis area and arrangement of antennas and iron bar

by arranging the T_x antenna with high-frequency current distribution on the surface of concrete.

In the FDTD method, a rectangular lattice, called a Yee lattice, is virtually placed in an analysis region [17]. The size of the Yee lattice in this study was 1 mm in both the x and y directions. Generally, the cell size should be set to below $1/10$ of a wavelength; this is about 100 mm for 3.0 GHz. In this simulation, the cell size was set to 1 mm to reproduce the cross-sectional shape of an iron bar. As the result, the total number of Yee lattices in the two-dimensional analysis region was 1132×632 . By impedance mismatching between free space and concrete, a considerable amount of reflected waves will be generated from the wall. There are several studies on reflection and transmission characteristics of microwaves inside concrete [18, 19]. According to these studies, the reflection coefficient in concrete is about 0.5 even in the case of vertically polarized incidence. In this study, to absorb reflected waves, a perfect matching layer (PML) 16 mm thick was provided at the edges of the two-dimensional analysis area [20, 21].

To investigate the influence of an iron bar on microwave propagation, the T_x antenna was placed at $(x, y) = (500, 0)$, and the power distributions of microwaves were obtained by FDTD simulation. Figure 9a shows the distribution in the absence of an iron bar, and Fig. 9b shows for an iron bar 32 mm in diameter buried at a depth of 300 mm. In these distributions, the power density is indicated by the index color as relative value. From this propagation pattern, it is considered that the direct wave radiated from the T_x antenna and the reflected wave on the surface of concrete interfere with each other and a standing wave with a complicated distribution pattern occurs inside the concrete. In addition, a weak region of intensity radially spreads out behind an iron bar. It is estimated that these intensity distributions change with the position and diameter of the iron bar.

To investigate whether the position information for an iron bar inside concrete can be obtained by measuring the power distribution of penetrated waves, first of all, we performed the calculation for concrete without an iron bar. As shown in the schematic drawing of Fig. 10a, the T_x and R_x antennas were moved in parallel along the surface of a uniform concrete wall. Dotted lines in the figure show geometric propagation directions of microwaves inside the concrete. Figure 10b shows the power distribution of a 1.2-GHz penetrated wave when the antennas travelled from $x = 20$ to 980 mm. A large fluctuation in power intensity was observed on both sides of the concrete block ($300 \leq x \leq 700$). However, that fluctuation decreased near the center. A wave that is directly reaching a receiving point from the T_x antenna and a wave arriving after one reflection on the side of concrete interfere with each other, as shown in Fig. 10a. This is the source of the fluctuation.

Fig. 9 Pattern of relative power density of 2.4-GHz wave: **a** without iron bar, **b** with iron bar 32 mm in diameter and 300 mm deep

The reflected wave arriving at the center of the concrete is weak due to a large incidence angle within the concrete and a long propagation path. Therefore, it is considered that the interference phenomenon with a direct wave did not appear clearly around the center. In contrast, on both sides, there is no large difference in intensities of the direct and reflected waves, so interference would be noticeable. Assuming the intended application, this fluctuation will become an obstacle when searching for iron bars near the end of wall. However, if the distance is at least about 400 mm from the end of wall, the fluctuation becomes very small, making it possible to locate an iron bar.

Next, we calculated the power distributions for the case of a buried iron bar. An iron bar with 32-mm diameter was arranged at the point $(x, y) = (500, 150)$, as shown in Fig. 11a. Figure 11b shows the of penetrated waves. For comparison, the profile for the block without an iron bar is indicated by a red line in the graph. At the position where an iron bar exists ($x = 500$), attenuation of about -7 dB occurred compared with the case of without an iron bar. Fluctuation in power density was observed at

Fig. 10 Transmitted power distributions of penetrated waves: **a** schematic illustration of an analysis area without iron bar, **b** power density distribution profile of 1.2-GHz wave penetration from the surface of homogeneous concrete

both ends of the concrete block ($x \leq 300$, $700 \leq x$) and these pattern are almost the same as that for the block without an iron bar. Therefore, the origin of fluctuation is considered to be interference between the direct and reflected waves. The valley seen in the profile is considered to be the point on the x -axis where iron bar exists; however, if this valley becomes broad, location accuracy will be worse. Therefore, we examined the relationship between microwave frequency and the valley shape (see Fig. 12). The transmission frequencies were set to 1.2 GHz, 2.4 GHz, and 4.8 GHz, and diameter and position of the iron bar were fixed at 32 mm and $(x, y) = (500, 300)$, respectively. The width of the valley narrowed as the frequency increased.

It is natural to think that width and depth of the valley are also affected by the thickness of the iron bar. Figure 13 shows the transmitted power distributions when the diameter of the iron bar changed over the range of 20–64 mm. Here, the transmission frequency and position of iron bar were fixed at 2.4 GHz and $(x, y) = (500, 300)$, respectively. The thick iron bar tended to increase the width and depth of the valley. Notable differences appeared, particularly in the depth of the valleys. A shallow valley might be hidden by the fluctuation.

Fig. 11 Transmitted power distributions of penetrated waves: **a** schematic illustration of analysis area with an iron bar embedded 150 mm deep, **b** power density distribution profiles of 1.2-GHz wave penetration from the surface of homogeneous concrete

Fig. 12 Transmitted power distributions of penetration of waves with different frequencies: 1.2 GHz, 2.4 GHz, and 4.8 GHz

For applying WPT to a robot, it is important that the system have the ability to detect an iron bar buried deep from a wall surface. In our system, because the sending/receiving relationship between the T_x and R_x antennas can be easily switched, for a wall 50 cm thick, the ability

Fig. 13 Transmitted power distributions of penetration of waves in concrete containing iron bars with different diameters. The transmission frequency of 2.4 GHz and the position of iron bar (x, y) = (500, 300) was fixed in all profiles

to search to a depth of 25 cm is required. In Fig. 14, the transmission frequency was fixed at 2.4 GHz, and the profiles were acquired by changing the burial depth of the iron bar ($50 \leq y \leq 400$). The valley was sharp when the bar was near the concrete surface ($y = 50$). However, the valley became broad for deeper positions, such as $y = 250$. Then,

Fig. 14 Transmitted power distributions of penetration of waves for different iron bar burial depths. Transmission frequency of 2.4 GHz and iron bar diameter of 32 mm was fixed for all profiles. Each profile was offset by -3 dB so that their shapes could be easily compared

the valley again sharpened for a bar that is shallow with respect to the opposite side of the wall, such as $y = 400$. Since the valley tends to be broad for deep bars, the ability to detect an iron bar will tend to deteriorate when the bar is deep. This simulation used a 2.4-GHz microwave, but it is better to use a higher frequency to improve the detection capability.

In this research, we assumed a maximum concrete wall thickness of 50 cm. However, the simulation results suggest that our system is adaptable to even thicker walls if a higher microwave frequency is used. Figure 15 shows the power distributions when the microwave frequency is 4.8 GHz and the wall thickness is 70 cm. Even when the burial depth is 350 mm, the valley seen in the profile is sharper than that for a burial depth of 250 mm. Therefore, using a higher frequency for thicker walls is considered to be effective for achieving high detection sensitivity.

In order to verify the reliability of the simulation results, an experimental investigation was performed. However, it was difficult to construct a wall the same size as that used in the simulation, so we fabricated a $400 \times 400 \times 400$ mm concrete block as shown in Fig. 16. Cylindrical iron bars with a diameter of 20 or 32 mm were embedded vertically in the block. We then attempted to determine the position of each bar by horizontally moving a pair of patch antennas impedance-matched at 1.2 GHz. Higher frequencies are expected to give better results, but unfortunately our instrumentation did not support higher frequencies than this. Figure 17 shows the power distributions obtained when the antennas were moved across a distance of 200 mm centered on the midpoint of the block. A clear valley is seen in the center of the scanned region ($x = 200$ mm) where the iron bar is present. The red

Fig. 15 Transmitted power distributions for 50 cm thick concrete wall. The transmission frequency was 4.8 GHz and the iron bar diameter was 32 mm in each case. Each curve is offset by -3 dB for easy comparison

Fig. 16 Cubic concrete block fabricated for iron bar detection test

Fig. 17 Transmitted power distributions for $400 \times 400 \times 400$ mm concrete blocks. The experiments were carried out using iron bars with diameters of 20 mm and 32 mm

simulated curve in Fig. 12 was calculated under the conditions closest to those for the red curve in Fig. 17, and there is seen to be good qualitative agreement between the simulation and experimental results. However, the valley in Fig. 17 is slightly narrower than that in Fig. 12, which may be because the concrete block used in the experiment was thinner than that in the simulation.

For a realistic application, such as when there are multiple iron bars in a wall, the ability to distinguish individual iron bars will be required. This ability makes it possible to place WPT couplers in the gap between two iron bars. Figure 18a is the power distribution profile when two iron bars were arranged at intervals of 100 mm at positions of $x = 450$ and 550 . Here, other calculation conditions were

Fig. 18 Transmitted power distributions of penetration of 1.2-GHz waves when two iron bars are buried inside the concrete: **a** diameter of iron bars was 20 mm, burial depth was 250 mm, and interval between iron bars was 100 mm; **b** diameter was 20 mm, depth was 250 mm, and interval was 200 mm

fixed as follows; 1.2 GHz, iron bar diameter of 20 mm, and burial depth of 250 mm. Under these conditions, we predicted that it would be difficult to identify the iron bars because valleys appearing in the profile are both shallow and broad. In fact, clear valleys were not seen at the positions of the iron bars. Figure 18b shows the results when the interval between the two iron bars was increased to 200 mm. We still could not see clear valleys. In conclusion, for low-frequency microwaves, such as 1.2 GHz, it can be said that it is difficult to distinguish individual iron bars when multiple bars are placed side by side.

Figure 19 shows the profiles when the transmission frequency was increased to 4.8 from 1.2 GHz and the iron bar diameter was increased to 44 from 20 mm. In this case, two valleys could be clearly distinguished in the profiles, and it was possible to distinguish individual iron bars, even at an interval of 100 mm. Moreover, even when the diameter was changed from 44 to 20 mm, clear valleys could be confirmed at the positions of iron bars. From these results, it will be possible to find the gap between iron bars by using high frequencies, such as 4.8 GHz. However, the coherency of microwaves inside concrete was preserved because our simulations assumed that the physical properties of concrete are uniform, but this would not be the case for actual concrete. In the future, it will be necessary to confirm whether similar profiles can be obtained by experiment. In addition, reflected waves arriving at the

Fig. 19 Transmitted power distributions of penetration of 4.8-GHz waves when two iron bars are buried inside the concrete: **a** diameter of iron bars was 44 mm, burial depth was 250 mm, and interval between iron bars was 100 mm; **b** diameter was 44 mm, depth was 250 mm, and interval was 200 mm

edges of the two-dimensional analysis region were completely absorbed by the PML. However, because in reality it would be difficult to prepare such a perfect absorbent, the influence of waves reflected from the edges needs to be confirmed by experiment.

4 Conclusions

In order to avoid placing WPT couplers close to iron bars embedded in concrete, we invested a means of determining the location of such bars using a pair of patch antennas. Numerical simulations were first carried out using the FDTD method for concrete walls up to 70 cm thick reinforced with iron bars with different diameters. The effectiveness of this system was then confirmed experimentally using $400 \times 400 \times 400$ mm concrete blocks. From the simulation results, it was found that a microwave frequency of 4.8 GHz is optimum for penetrating concrete walls thicker than 50 cm, and also for distinguishing between multiple embedded iron bars. These findings are expected to be useful for performing WPT through a reinforced concrete wall.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

- Ishida H, Kyoden T, Furukawa H (2018) Super-low-frequency wireless power transfer with lightweight coils for passing through a stainless steel plate. *Rev Sci Instrum* 89:034706-1–034706-11
- Zhang J-K, Yang W, Cui D-M (2016) Concrete condition assessment using impact-echo method and extreme learning machines. *Sensors* 16(4):447-1–447-17
- Yeh P-L, Liu P-L, Hsu Y-Y (2018) Parametric analysis of the impact-echo phase method in the differentiation of reinforcing bar and crack signals. *Constr Build Mater* 180:375–381
- Chang CW, Lin CH, Yuan Q-W (2018) Quantitative study of electromagnetic wave characteristic values for mortar's crack. *Constr Build Mater* 175:351–359
- Lachowicz J, Rucka M (2018) 3-D finite-difference time-domain modeling of ground penetrating radar for identification of rebars in complex reinforced concrete structure. *Arch Civ Mech Eng* 18:1228–1240
- Carrara P, Kruse R, Bentz DP, Lunardelli M, Leusmann T, Varady PA, De Lorenzis L (2018) Improved mesoscale segmentation of concrete from 3D X-ray images using contrast enhancers. *Cem Concr Compos* 93:30–42
- Skarżyński Ł, Suchorzewski J (2018) Mechanical and fracture properties of concrete reinforced with recycled and industrial steel fibers using digital image correlation technique and X-ray micro computed tomography. *Constr Build Mater* 183:283–299
- See <http://www.jrc.co.jp/eng/product/lineup/njj105/pdf/NJJ-105.pdf> for information about a RC radar system
- Bouhamla MA, Beroual A (2017) Experimental characterization of concrete containing different kinds of dielectric inclusions through measurements of dielectric constant and electrical resistivity. *Procedia Environ Sci* 37:647–654
- Jenkinson MJ, Banks JW (2018) High-order accurate FDTD schemes for dispersive Maxwell's equations in second-order form using recursive convolutions. *J Comput Appl Math* 336:192–218
- Bao W, Teixeira FL (2018) Performance analysis of perfectly matched layers applied to spherical FDTD grids. *IEEE Trans Antennas Propag* 66:1035–1039
- Wang T-Y, Chen CCP (2003) Thermal-ADI—a linear-time chip-level dynamic thermal-simulation algorithm based on alternating-direction-implicit (ADI) method. *IEEE Trans VLSI Syst* 11:691–700
- Shoji M (1995) Heat transfer textbook, University of Tokyo Series on advanced mechanical engineering, vol 6. University of Tokyo Press, Tokyo
- Ishida H, Furukawa H (2015) Wireless power transmission through concrete using circuits resonating at utility frequency of 60 Hz. *IEEE Trans Power Electron* 30:1220–1229
- Ishida H, Furukawa H, Kyoden T, Tanaka T (2017) Development of a wireless power transmission simulator based on finite-difference time-domain using graphics accelerators. *IET Power Electron* 10:1889–1895
- Ishida H, Furukawa H, Kyoden T (2016) Development of design methodology for 60 Hz wireless power transmission system. *IEEJ J Ind Appl* 5:429–438

17. Yee K (1966) Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *IEEE Trans Antennas Propag* 14:302–307
18. Bois KJ, Benally AD, Zoughi R (2000) Microwave near-field reflection property analysis of concrete for material content determination. *IEEE Trans Instrum Meas* 49:49–55
19. Chung KL, Kharkovsky S (2015) Monitoring of microwave properties of early-age concrete and mortar specimens. *IEEE Trans Instrum Meas* 5:1196–1203
20. Berenger JP (1994) A perfectly matched layer for the absorption of electromagnetic waves. *J Comput Phys* 114:185–200
21. Roden JA, Gedney SD (2000) Convolution PML (CPML): an efficient FDTD implementation of the CFS-PML for arbitrary media. *Microw Opt Technol Lett* 27:334–339

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