Nondestructive evaluation of air voids in concrete structures using microwave radar technique

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ABSTRACT

Nondestructive inner inspection techniques are essential to certify the safety or health of concrete structures, and one of the important issues in these inspections is the detectability of thin air voids or cracks. In this study, we propose a novel method for discriminating the variety and estimating the thickness of air voids based on the microwave radar technique. Specifically, to distinguish air voids from other objects, the phase shift of the microwaves was analysed using time-frequency analysis. In addition, based on a simple parallel incidence model, microwave reflection and refraction analysis were conducted on homogeneous layers, and a particular relation was calculated between the reflectance and the air void thickness. The experimental performance of the functions to distinguish air voids was good, however, quantitative thickness estimation failed. Therefore, we introduced a novel sophisticated propagation path model based on ray-traced propagation, which provides a couple of propagation paths. Additionally, the attenuation feature of microwaves was also considered. A quantitative thickness estimation method was re-applied to the experimentally observed waveforms. The estimation accuracy improved by approximately 54%, and the validity of quantitative thickness estimation was confirmed.

1. Introduction

In Japan, concrete structures built during the rapid economic growth period about 50 years ago are aging, and their maintenance and management have rapidly become a social problem. Accidents related to infrastructure buildings have significant influence and directly lead to human suffering. In particular, the safety and security of concrete structures such as piers and buildings have been emphasized in recent years, and the diagnosis of abnormalities that occur as a result of deterioration of these structures has been recognized as an extremely important issue [1]. The phenomena to be diagnosed in concrete structures can be divided into several types. The specific examples are: corrosion of the reinforcing bars inside the concrete structure, deterioration of concrete itself (neutralization), delamination or cracking inside concrete, and so on [2]. In tunnel structures and so on, the diagnosis of gaps and cavities on the underside of concrete is also an important issue [3]. It is desirable that the techniques for diagnosing such abnormalities detect the presence or absence of abnormalities non-destructively and also, quantitatively evaluate the type and size of the abnormality [4].

Regarding non-destructive diagnostic technique to evaluate the deterioration of the concrete structures, the popular methods include usage of X-ray transmission or electromagnetic induction. In addition, elastic waves such as ultrasonic waves, electromagnetic pulses, and elastic shock waves are also used to evaluate the deterioration of the reinforcing bars and so on [5–7]. For fundamental reasons, it is difficult to estimate the cover thickness (depth) of an object using the X-ray transmission method, and it is impossible to detect non-metal objects using the electromagnetic induction method. Moreover, in the methods using elastic waves, information on the propagation speed and the frequency spectrum of the waves propagating in concrete is used to evaluate the strength and defects of concrete structures. However, in these methods, the elastic waves are also affected by the condition inside the concrete, and it is difficult to identify only the information of the deterioration related to a specific diagnosis target (such as a reinforcing bar) from the information obtained from the observed waveforms. Each method has its own problems, and the establishment of a determinate technique is urgently required.

The microwave radar technique, which is the focus of this study, is one of the techniques used in the diagnosis of concrete structures [6]. Owing to its diagnostic principle that focuses on the reflected microwave waves, it can detect non-metal objects and estimate the depth of the object, and it is not susceptible to the propagation path of microwaves. Hence, there are many examples of
research and development on visualization techniques combined with antenna arrays [8] and position estimation systems [9], and there is also the need to achieve a quantitative estimation of deterioration such as reinforcing bars or voids inside concrete structures [10]. In addition, deep learning has also been applied to identify objects and abnormal regions inside concrete structures from commercial radar images [11–13]. However, for air voids or cracks inside concrete structures, the amplitude of the reflected microwave is very small because they are often very thin. Therefore, in related studies based on the microwave radar technique, the waveforms reflected on air voids or cracks are regarded as measurement noise, and they are often not discussed as the phenomena to be diagnosed [14–16]. As mentioned above, the diagnosis of air voids or cracks is one of the most important issues, and it would be advantageous to diagnose them together with the deterioration of other entities such as the steel bars using the microwave radar technique.

On the imaging and evaluation of the position and size of reflected objects inside concrete structures using the microwave radar technique, the propagation of microwaves is modelled based on the principle of ray tracing [16–18]. The propagation time information of a waveform of the reflected microwave is converted to depth information, and it is back-projected to the exploration area based on the model, and the effectiveness of this method has been confirmed [19,20]. In addition to information on the propagation time, the waveform of the reflected microwave also contains information of the amplitude and phase, which fluctuate depending on the difference in the electrical characteristics between the reflective object and concrete. If such information can be extracted and utilized, it may be possible to precisely estimate not only the position and size of the reflective object or the abnormal region, but also their shapes, materials, or states of deterioration [21–23]. Precise signal processing techniques for reflected waveforms have been studied for this purpose [24–27].

In this study, we focus on the evaluation of thin air voids or cracks that occur inside or on the backside of concrete structures. Based on the propagation time, amplitude, and phase shift information that can be extracted from the waveforms of the reflected microwaves, we propose a novel methodology to achieve two functions, i.e. distinguish thin air voids or cracks from other objects, and quantitatively estimate their thickness. By referring to the phase shift information of the reflected waveform, we can distinguish the air layers (air voids or cracks) from other objects. The thickness of the identified air layer is estimated based on the amplitude information of the reflected waveform. Specifically, an interference model of the reflected microwaves on the upper and lower boundaries of the air layer is introduced to explain the amplitude fluctuation of the reflected waveform in relation to the thickness of the air layer. Quantitative estimation of the thickness of the air layer has been conducted using this relationship.

The remainder of this paper is organized as follows. In Section 2, a fundamental discussion of the microwave radar technique is provided, and in Section 3, we present interesting experimental results confirming the reflection phenomenon of microwaves against thin air layers. In Section 4, a quantitative estimation of the air layer thickness is presented by introducing an interference model of the reflected microwaves on the boundaries of the air layer. In Section 5, a detailed interference model based on the microwave propagation model is proposed to improve the accuracy of air layer thickness estimation. Finally, Section 6 concludes the paper and discusses future research avenues.

2. Microwave radar survey

2.1. Nondestructive inner inspection using microwave radar technique

The fundamental principle of the microwave radar technique is illustrated in Figure 1. The radar antenna unit, which has built-in transmitter and receiver units, is scanned on the surface of the survey target, while repeating the transmission and reception of microwaves in sequence, as shown in Figure 1(a). A transmitted microwave propagates along a minimal-length propagation path and is reflected on the interface of the dielectric constant inside the survey target, as shown in Figure 1(b). Accordingly, an observed microwave data set is obtained.

Microwave propagation length data are derived from round-trip propagation time data \( t \) at each observation point. Subsequently, the positions and shapes of the buried objects are estimated. The depth \( d \) of a buried object is derived by the following equation:

\[
d = \frac{l}{2} = \frac{c_0 t}{2\sqrt{\varepsilon_r}}
\]

where \( l \) is the microwave propagation length, \( c_0 \) is the speed of light in the void, and \( \varepsilon_r \) is the relative permittivity of the propagation medium. It is calculated as half of the microwave propagation length in the perpendicular direction.

The antenna apparatus of an actual microwave radar antenna unit is a bi-static configuration [20] on which the transmitter and receiver are separated. Nevertheless, considering the mono-static configuration model of the transmitter and receiver and perpendicularly oriented superdirective property of the microwave, an internal cross-sectional radar image, i.e. a B-mode radar image, which is generally used for inner concrete inspection, is drawn using the estimated depth.
data $d$. As it is difficult to grasp the minute position or shape of a buried object from this inaccurate B-mode radar image, a more specific signal processing method is essential.

### 2.2. Analysis method of reflected microwaves

To estimate the amplitude and phase shift of the reflected microwaves with high accuracy, the wavelet transform approach is applied \[28\]. The wavelet transform is a time-frequency analysis technique, and as is generally known, its definitional equation \[W\] is expressed as

$$W(a_w, b_w) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{a_w}} x(t) \psi \left( \frac{t-b_w}{a_w} \right) dt \quad (2)$$

where $x(t)$ is an input signal, $\psi(t)$ is the mother wavelet function, $a_w$ is a time scale parameter that corresponds to the frequency element of the mother wavelet function, and $b_w$ is a time shift parameter.

Additionally, the mother wavelet function used for the analysis of observed microwaves in this study is the Gabor wavelet function, which is expressed by \(3\).

$$\psi(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{t^2}{2\sigma^2}} e^{j\omega_0 t} \quad (3)$$

It is expressed by a multiplication of the Gaussian window and the complex trigonometric function. Therefore, in \(3\), $\sigma$ is the width of the Gaussian window, which is set to 0.5, and the inverse of $a_w$ indicates the frequency of the complex trigonometric function when $\omega_0$ is fixed at $2\pi$. Consequently, the time-scale $a_w$ corresponds to the time period.

As the amplitude of $W$ becomes maximum when the correlation between the observed microwave $x(t)$ and the mother wavelet function $\psi(t)$ becomes maximum, we can recognize that the reflected microwave has been clipped. Then, the time shift $b_w$ and the amplitude of the complex number $W(a_w, b_w)$ are assumed as the propagation time $\hat{t}_w$ and the amplitude $\hat{A}_w$ of the reflected microwave, respectively. In addition, the argument of the complex number $W(a_w, b_w)$ also assumes the phase shift $\hat{\phi}_w$ of the reflected microwave.

### 2.3. Amplitude and phase shift variance on reflected microwaves

The amplitude of the reflected microwaves may also vary depending on the principles of microwave attenuation, reflection, transmission, etc. Meanwhile, when a microwave enters perpendicular to an interface of the dielectric constant, i.e., perpendicular to the surface of a buried object in the propagation medium, it is well known that the sign of the reflected microwave changes depending on the relative permittivity of the propagation medium and that of the buried object based on the Fresnel’s formula. Specifically, when the relative permittivity of the buried object is smaller than that of the propagation medium, the sign of the reflected microwave does not change and vice versa for the reverse case.

This phenomenon is closely responsible for buried object surveys. Figure 2 shows the schematic differences of microwaves between the transmitted wave and the reflected wave when the propagation medium is concrete and the buried object is a resin or a metal. On occasions when the buried object is resin, as its relative dielectric constant is smaller than that of concrete, no sign change is observed in the reflected wave, or the phase shift becomes 0°. However, in the case of metal, as the relative dielectric constant is larger than that of concrete, the sign of the reflected wave is inverted with respect to the transmitted wave, or the phase shift becomes 180°.

In an actual environment, the microwave incidence angle on the buried object is not always perpendicular to its surface boundary. As the phase shift characteristics are slightly dependent on the microwave incidence angle, in previous studies, it has been shown that a phase shift trend of reflected microwaves may lead to
3. Experimentally observed microwaves for different air void thicknesses

3.1. Experimental setup and environment

In this study, a controller of a microwave radar system (SIR-2000) and a dedicated antenna unit (Model5100) fabricated by GSSI Inc. were employed as the microwave radar system. The photographs are shown in Figure 3. The antenna unit was connected to the controller, and the microwaves were observed with regulated time-interval transmission and reception functions. The dominant specifications of the radar system were as follows. The nominal centre frequency of the microwave antenna unit was 1.2 GHz. In addition, the measuring time range was 8.0 ns, the time resolution was 0.02 ns, and the scan time rate was 32 scan/s.

A photograph and a schematic of the experimental environment are shown in Figure 4. As shown in Figure 4(a), there were six accumulated concrete plates, each of thickness 60 mm. The depth and thickness of the air void could be set by shutting thin boards into a space between two arbitrary adjacent concrete plates, and hereby adjusting the gap height, as shown in Figure 4(b). In particular, the buried depth of the air void was set to 60 or 120 mm, and the air void thickness ranged from 2.4 to 28.8 mm at each buried depth. The relative permittivity of concrete and air was assumed to be approximately 9.0 and 1.0, respectively.

3.2. Observed microwaves

The experimental procedure of reflected microwave acquisition is indicated below.

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Figure 2. Difference of reflected microwave depending on material of buried object in concrete: (a) Resin and (b) Metal.

Figure 3. Photographs of the microwave radar system: (a) SIR-2000 (Controller) and (b) Model5100 (Antenna).

Figure 4. Experimental environment: (a) photograph of the concrete test specimen and (b) schematic of the air void in the propagation medium.
Figure 5. Reflected microwaves from air voids: (a) the depth of air voids was 60 mm and (b) the depth of air voids was 120 mm.

(1) In order to create an initial 2.4 mm air void, thin boards of the same thickness were sandwiched between the first and second concrete plates on either side.

(2) We observed the reflected microwaves using the microwave radar system.

(3) The accumulated quantity of sandwiched thin boards was adjusted to increase the void thickness.

(4) Steps (2) and (3) were repeated with a gradual increase in the air void thickness from 2.4 to 28.8 mm in steps of 2.4 mm.

These procedures were performed for air void buried depths of 60 and 120 mm.

The reflected microwaves from the air void are selectively shown in Figure 5, and the captioned length values in each graph area indicate the set air void thickness. The estimated amplitudes of all the reflected waves are shown in Figure 6. When the thickness of the air void is increased, the amplitude of the reflected microwave also increases, and we clarify that the amplitude of the reflected microwave is related to the thickness of the air void. In other words, a monotonic increase can be found between these two variables, and the possibility of quantitative estimation of air void thickness has been found based on these relationships.

4. Discrimination and quantitative thickness estimation of air voids

4.1. Assumption: interference of microwaves

To solve the problem of quantitative thickness estimation, an assumption of microwave interference is introduced. The relative permittivity of concrete is determinately larger than that of air. Therefore, we could simulate the reflected waveforms from the upper and lower boundaries based on the Fresnel’s formula and the equation of microwave propagation velocity \( v = \frac{c_0}{\sqrt{\varepsilon_r}} \). Hence, the phase shift of the reflected waveform on the perpendicular directed microwave from the upper concrete–air interface was 0°, whereas that from the lower air–concrete interface was 180°.

Figure 7 shows the simulated reflected waveforms from the air void buried at a depth of 60 mm, each of which was calculated by superposing the reflected waveforms from the upper and lower boundaries. The captioned length values in the graph areas represent the true values of the air void thicknesses. It may be noted that the amplitudes of the simulated waveforms were gradually increased, similar to the experimental waveforms. However, the absolute amplitude values do not conform to the experimental values, and more precise modelling of microwave reflection is needed to quantitatively estimate the air void thickness.
4.2. Quantitative thickness estimation method based on parallel incidence model

A parallel incidence model has been discussed based on the principles of microwave reflection and refraction, to consider the interference of microwaves. Figure 8 shows a schematic of microwave incidence, reflection, and refraction on homogeneous concrete–air–concrete layers. The refractive index of air is set to $n_1$, that of concrete is set to $n_2$. A distance $h$ is the air void thickness, and the incidence angle of microwaves on the upper boundary is $\alpha$, which is defined based on the air void depth $d$ and the geometrical separation distance $L$ between the microwave incidence and output points. Additionally, the incidence angle on the lower boundary is $\beta$, which is equivalent to the refraction angle on the upper boundary, is expressed by the following equation:

$$\beta = \sin^{-1}\left(\frac{n_2}{n_1} \sin \alpha\right)$$

When the integrated reflectance of the air void is assumed to be $R$, $R$ can be calculated from the principle of optics. The reflectivity of upper and lower air interfaces is set as $r_{ca}$ and $r_{ac}$, respectively. Based on the Fresnel’s formula, $r_{ca}$ and $r_{ac}$ are expressed by the following equations:

$$r_{ac} = \frac{n_2 \cos \alpha - \sqrt{n_1^2 - n_2^2} \sin \alpha}{n_2 \cos \alpha + \sqrt{n_1^2 - n_2^2} \sin \alpha}$$

$$r_{ca} = \frac{n_1 \cos \beta - \sqrt{n_2^2 - n_1^2} \sin \beta}{n_1 \cos \beta + \sqrt{n_2^2 - n_1^2} \sin \beta}$$

In addition, the phase shift $\delta$ is defined geometrically using (7).

$$\delta = \frac{2\pi}{\lambda_0} n_1 h \cos \beta$$

where $\lambda_0$ is the wavelength of the microwave in the void. Taking all multipath reflection into account, finally, the integrated reflectance $R$ of the air void is conducted using the following equation:

$$R = \left| r_{ca} + r_{ac} e^{i\Delta \delta} \right|^2 = r_{ca}^2 + r_{ac}^2 + 2 r_{ca} r_{ac} \cos 2\delta$$

There is a particular relation between the air void thickness $h$ and the integrated reflectance $R$ of the air void in (8).

An example of application of this relation is shown in Figure 9, where the horizontal and vertical axes represent the air void thickness $h$ and the integrated reflectance of air void $R$, and 40 mm has been adopted as a value of the distance, empirically. In addition, the blue and orange curves express the difference in the air void depth, i.e. the blue curve represents a depth of 60 mm, and the orange curve represents a depth of 120 mm. As the experimental reflectance is derived from the amplitude of the reflected microwave divided by that of the incident microwave, the air void thickness $h$ can be estimated from the experimental reflectance based on the relation expressed by (8).

4.3. Experimental evaluation of air voids

4.3.1. Evaluation procedure

A procedure of quantitative evaluation of air voids is indicated below.

1. Obtain the reflected microwave from the air void
2. Compute the maximum amplitude $\hat{A}_w$, the propagation time $\hat{t}_w$, and the phase shift $\hat{\phi}_w$ of the reflected microwave
3. Distinguish the air void using the computed phase shift $\hat{\phi}_w$
4. Estimate the air void depth $d$ using the computed propagation time $\hat{t}_w$ and calculate the theoretical reflectance curve
5. Calculate the experimental reflectance by dividing the computed amplitude $\hat{A}_w$ by the amplitude of the incident microwave
6. Estimate the air void thickness $\hat{h}$ using the theoretical reflectance curve.
These procedures were repeated with a gradual increase in the air void thickness from 2.4 to 28.8 mm in steps of 2.4 mm. In addition, the experimentally estimated values of 250 mm, 13490, and 40.0 mm were assigned to the microwave wavelength in the void, the amplitude of the incident microwave, and the geometrical separation distance between the microwave incidence and output points, respectively.

4.3.2. Discrimination results of air voids

The computed parameters of the reflected microwaves observed by the receiver at the air void depths of 60 and 120 mm are shown in Tables 1 and 2. First, at the same buried depth, when the air void thickness is larger, the propagation time \( \hat{t}_w \) is also gradually and slightly longer. It is inferred that the reflected wave on the lower air void boundary causes interference.

Even though the phase shift values are not completely the same, they are almost in the range of \(-25^\circ\) to \(-80^\circ\). A comparison of the averaged phase shift values between several buried objects, such as metal or resin, is shown in Table 3. The data of metal and PVC have been quoted from previous research document by Hagiwara et al. [29], and each value of the air void is the averaged value for different air void thicknesses. The phase shifts of the air void and those of the metal and PVC are evidently different from each other. Therefore, it is possible to discriminate the air void selectively by focusing on the phase shift value of the reflected microwave.

Table 1. Computed parameters by the wavelet transform method for depth 60 mm.

| Thickness [mm] | \( A_w \) [–] | \( \hat{t}_w \) [ns] | \( \hat{\phi}_w \) [deg] |
|---------------|----------------|-----------------|------------------|
| 2.4           | 1122           | 1.023           | 167.26           |
| 4.8           | 1825           | 1.148           | 137.90           |
| 7.2           | 2387           | 1.262           | 86.85            |
| 9.6           | 2893           | 1.293           | 73.46            |
| 12            | 3511           | 1.289           | 73.90            |
| 14.4          | 3843           | 1.313           | 63.14            |
| 16.8          | 4351           | 1.316           | 61.80            |
| 19.2          | 4645           | 1.332           | 58.80            |
| 21.6          | 4958           | 1.344           | 54.63            |
| 24            | 5256           | 1.352           | 53.71            |
| 26.4          | 5533           | 1.352           | 54.00            |
| 28.8          | 5650           | 1.359           | 53.18            |

Table 3. Comparison of experimentally computed phase shift value.

| Material     | Depth = 60 mm | Depth = 120 mm |
|--------------|---------------|----------------|
| Aluminium    | 120.7         | 126.3          |
| Rusted iron  | 123.2         | 108.5          |
| PVC          | -16.3         | -17.3          |
| Air void     | -50.3         | -31.6          |

4.3.3. Quantitative estimation results of air void thickness

First, the estimation of air void depth \( d \) has been conducted with the averaged computed propagation time, and the values of 59.7 and 125.5 mm are estimated for the true buried depths of 60 and 120 mm, respectively. The estimated results for the buried depth are comparatively good.

Subsequently, the theoretical integrated reflectance values and the experimental values of the reflected microwaves from air voids have been compared. Figure 10 shows the reflectance values of the reflected microwaves, and the blue and orange symbols express the differences in the air void depth, as discussed previously. The horizontal and vertical axes represent the air void thickness and reflectance, respectively. The amplitude of the reflected microwave increases with an increase in the thickness of the air void, and this phenomenon corresponds to the fundamental experimental results described in Section 3.2.

A quantitative estimation of the air void thickness has been conducted based on an inverse estimation approach from the experimental reflectance. The estimation results of the air void thickness at the air void depth of 60 and 120 mm are presented in Tables 4 and 5, respectively. The estimation error \( \Delta h \) at the depth of 60 mm ranges from approximately 7 to \(-2\) mm, and that at the depth 120 mm ranges from 4 to \(-10\) mm. The estimated thicknesses are larger than the actual values up to an air void thickness of approximately 20 mm on the depth of 60 mm and 15 mm on the depth of 120 mm. Conversely, they are smaller than actual values when the air void thickness is set to more than approximately 20 and 15 mm, respectively. The RMSE values

Figure 10. Comparison of reflectance between estimated and experimental values.
Table 4. Estimation results of air void thickness for depth 60 mm.

| h [mm] | Reflectance [-] | \( \hat{h} \) [mm] | \( \Delta h \) [mm] |
|--------|-----------------|-----------------|-----------------|
| 2.40   | 0.083           | 9.17            | 6.77            |
| 4.80   | 0.135           | 12.09           | 7.29            |
| 7.20   | 0.177           | 14.20           | 7.00            |
| 9.60   | 0.214           | 18.23           | 6.23            |
| 12.00  | 0.260           | 19.38           | 4.98            |
| 14.40  | 0.305           | 21.60           | 4.46            |
| 16.80  | 0.344           | 23.54           | 3.15            |
| 19.20  | 0.388           | 25.84           | 1.94            |
| 21.60  | 0.420           | 27.12           | 0.72            |
| 24.00  | 0.451           | 28.43           | −0.56           |
| 26.40  | 0.483           | 29.75           | −2.47           |

Table 5. Estimation results of air void thickness for depth 120 mm.

| h [mm] | Reflectance [-] | \( \hat{h} \) [mm] | \( \Delta h \) [mm] |
|--------|-----------------|-----------------|-----------------|
| 2.40   | 0.028           | 6.61            | 4.21            |
| 4.80   | 0.045           | 8.28            | 3.48            |
| 7.20   | 0.071           | 10.63           | 3.43            |
| 9.60   | 0.093           | 12.39           | 2.79            |
| 12.00  | 0.100           | 12.90           | 0.90            |
| 14.40  | 0.128           | 14.88           | 0.48            |
| 16.80  | 0.134           | 15.27           | −1.53           |
| 19.20  | 0.150           | 16.33           | −2.87           |
| 21.60  | 0.163           | 17.30           | −4.30           |
| 24.00  | 0.183           | 18.53           | −6.79           |
| 26.40  | 0.187           | 18.82           | −9.98           |

4.4. Discussion regarding the estimation of air void thickness

We confirm that the proposed method can quantitatively estimate the air void thickness with acceptable accuracy. In other words, we confirm the validity of the principle of quantitative estimation of air void thickness by focusing on the integrated reflectance of air voids. However, the RMSE values are not small from a practical viewpoint, and the ranges of the estimation error are similar for both depths of 60 mm and 120 mm.

One of the causes is the lack of consideration of microwave attenuation. In this estimation, we assumed the amplitude of the direct wave on the receiver as that of the incident wave. Practically, in an actual experimental environment, there is a thick concrete layer between the antenna and the air void boundary. Nevertheless, the microwave attenuation on this layer has not been considered. In addition, it is our opinion that the parallel incidence and reflection & refraction model of microwaves is overly simplistic to accurately estimate the air void thickness.

5. Improvement in air void thickness estimation accuracy

5.1. Synthesized reflectance based on microwave propagation path model

5.1.1. Microwave propagation path model for air voids

The microwave propagation path model, which we have proposed in the previous study [28] is based on ray tracing, i.e. microwave refraction and specular reflection, and its extended version is applied for air void thickness estimation in this study. Figure 11 shows an extended microwave propagation path model in which a microwave refracts and reflects on three interfaces. The distance \( f \) is the separation length between the transmitter and receiver from a centre of the antenna unit, and a thin layer that is located immediately below the transmitter and receiver is the substrate of the antenna unit. The refractive indices of the substrate, air, medium 1, 2, and 3 are set as \( n_0, n_1, n_2, n_3, \) and \( n_4, \) respectively, and the thicknesses of the substrate layer, air layer, and medium 1 and 2 are \( d_0, d_1, d_2, \) and \( d_3, \) respectively.

The microwave oscillated by the transmitter propagates in these layers, and it is refracted and reflected on several interfaces of the media, and definitely received by the receiver. According to geometric alignment and Snell’s law, (9) and (10) can be written.

\[
f = \sum d_i \tan \theta_i \quad (9)
\]

\[
\theta_{i+1} = \sin^{-1}\left(\frac{n_i}{n_{i+1}} \sin \theta_i\right) \quad (10)
\]

Figure 11. Extended microwave propagation path model.
where $\theta_i$ is the microwave incidence angle on the $(i\text{th})$ interface between the homogeneous $(i+1)\text{th}$ and $i\text{th}$ layered medium, and it equals the microwave refraction angle on the interface between the $(i)\text{th}$ and $(i-1)\text{th}$ layered medium. When the reflectivity on the $(i)\text{th}$ interface is always set $r_{(i)(i+1)}$, based on Fresnel’s formula, they are expressed by the following equation:

$$r_{(i)(i+1)} = \frac{n_i \cos \theta_i - \sqrt{n_{i+1}^2 - n_i^2 \sin^2 \theta_i}}{n_i \cos \theta_i + \sqrt{n_{i+1}^2 - n_i^2 \sin^2 \theta_i}}$$ (11)

### 5.1.2. Introduction of bi-path model of microwave propagation

To improve the accuracy of air void thickness estimation, we have introduced a novel bi-path model of microwave propagation, which is an additional extended version of the propagation path model described in Section 5.1.1. Figure 12 shows a schematic of the bi-path model in which the propagation paths of reflected microwaves on the upper and lower air void boundaries differ from each other.

In this case, the reflectivity of the upper air void boundary $r_u$ and that of the lower air void boundary $r_l$ are similarly obtained by the following equations:

$$r_u = \frac{n_2 \cos \theta_{U2} - \sqrt{n_1^2 - n_2^2 \sin^2 \theta_{U2}}}{n_2 \cos \theta_{U2} + \sqrt{n_1^2 - n_2^2 \sin^2 \theta_{U2}}}$$ (12)

$$r_l = \frac{n_1 \cos \theta_{L3} - \sqrt{n_2^2 - n_1^2 \sin^2 \theta_{L3}}}{n_1 \cos \theta_{L3} + \sqrt{n_2^2 - n_1^2 \sin^2 \theta_{L3}}}$$ (13)

where $\theta_{U2}$ and $\theta_{L3}$ are the microwave incidence angles on the upper air void boundary and lower air void boundary, respectively. The phase shift $\delta_b$, which results from the extra microwave propagation length in the air void on the lower propagation path, is defined by the following equation:

$$\delta_b = \frac{2\pi}{\lambda_0} n_1 \frac{d_3}{\cos \theta_{L3}}$$ (14)

Finally, the synthesized reflectance $R_b$ can be derived based on the principle of optics and is expressed by the following equation:

$$R_b = \frac{\left|r_u + r_l e^{j2\delta_b}\right|^2}{1 + r_u r_l e^{j2\delta_b}} = \frac{r_u^2 + r_l^2 + 2r_u r_l \cos 2\delta_b}{1 + r_u^2 r_l^2 + 2r_u r_l \cos 2\delta_b}$$ (15)

(15) indicates the integrated reflectance of the entire air void. In this instance, we assume that behaviour of the microwaves on the upper and lower propagation paths in the layers located on the upper side of the air void are fairly identical each other, because the air void thickness $d_3$ is set as very thin.

### 5.2. Attenuation feature of microwaves in concrete

In the bi-path model of microwave propagation, attenuation of microwaves, which is caused by propagation, has been additionally considered. The attenuation coefficient was fixed experimentally in this study. Figure 13 shows the experimental amplitude of the microwaves in the concrete medium and its approximated curve using the exponential function.

As the microwave propagation length is shorter than the wavelength of the microwaves in the concrete medium, we have performed modelling with the attenuation formula of light and not Friis’ transmission equation. The absorption index $\alpha$ was set to 5.497 based

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**Figure 13.** Amplitude of microwaves in concrete.

**Figure 12.** Bi-path model of microwave propagation for air void evaluation.
on an approximation result. Therefore, the attenuation coefficient $\eta$ was calculated by the following equation:

$$\eta = e^{-\alpha(x_2 - x_1)} = e^{-\alpha x} \quad (16)$$

where the microwave propagation distances are $x_1$ and $x_2$, and the distance $x = x_2 - x_1$.

Meanwhile, attenuation in the substrate layer and air was not considered. The reasons are as follows. In the substrate layer and air, the wavelength of the microwave becomes approximately three times as long as that in concrete. As the attenuation of microwaves becomes small when the wavelength becomes long, the transmission gain in these layers is approximately nine times larger than that in concrete. In addition, the propagation lengths in the substrate layer and air are very short. Practically, the propagation lengths in these layers are 1/4–1/20 compared to those in the concrete layer. Therefore, the transmission gain is 16–400 times.

5.3. Theoretical relation between air void thickness and amplitude ratio

The theoretical amplitude ratio curves $\eta R_b$ for the bi-path model are shown in Figure 14. The horizontal and vertical axes represent the air void thickness and amplitude ratio, respectively.

In addition, in Table 6, the applied parameters of the experimental setup and experimental environments are shown. The amplitude ratio should correspond to the amplitude of the experimental reflected microwave divided by that of the preliminarily defined incident microwave.

![Figure 14. Theoretical amplitude ratio curve for the bi-path model.](image)

Table 6. Additional parameters of the experimental setup and environment.

| Parameter                        | Value |
|----------------------------------|-------|
| Separation length of antenna $f$ [mm] | 52.0  |
| Thickness of substrate layer $d_0$ [mm] | 1.2   |
| Thickness between antenna and concrete $d_1$ [mm] | 3.3   |
| Refractive index of substrate $n_0$ | 1.64  |

5.4. Estimation of air void thickness

5.4.1. Experimental amplitude ratio of reflected microwave

A procedure of quantitative estimation of air void thickness is indicated below.

(1) Obtain the reflected microwave from the air void
(2) Compute the maximum amplitude $\hat{A}_w$ and the propagation time $\hat{t}_w$ of the reflected microwave
(3) Estimate the air void depth $d_2$ based on the computed propagation time $\hat{t}_w$, and calculate the theoretical amplitude ratio curve
(4) Calculate the experimental amplitude ratio by dividing the computed amplitude $\hat{A}_w$ by the amplitude of the incident microwave
(5) Estimate the air void thickness $\hat{h}$ using the theoretical amplitude ratio curve.

These procedures were repeated with a gradual increase in the air void thickness from 2.4 to 28.8 mm. In addition, the amplitude of the preliminarily defined incident microwave is set as 13490 [–], as in the previous experiments.

5.4.2. Quantitative estimation results of air void thickness

The experimental and theoretical amplitude ratio values were compared, and the results are shown in Figure 15. The horizontal axis expresses the thickness of the air void, and the vertical axis expresses the amplitude ratio. All experimental amplitude ratio values at the depth of 60 and 120 mm correspond better to the theoretical values calculated based on the bi-path model than those based on the parallel incidence model. In particular, when the experimental condition of the air void depth is set to 120 mm, an accuracy of the experimental amplitude ratio values is considerably improved.

Table 7 shows the quantitative estimation results of the air void thickness using the data shown in Figure 15. The thickness estimation error $\Delta h$ ranges from $-4.3$ to 1.0 mm and $-1.2$ to 3.1 mm under the air void depths

![Figure 15. Comparison between theoretical and experimental amplitude ratio values.](image)
Table 7. Estimated air void thickness.

| Depth = 60 mm | Depth = 120 mm |
|--------------|---------------|
| h [mm] | \(\bar{h}\) [mm] | \(\Delta h\) [mm] | h [mm] | \(\bar{h}\) [mm] | \(\Delta h\) [mm] |
| 2.4 | 3.4 | 1.0 | 5.2 | 2.8 |
| 4.8 | 5.8 | 1.0 | 7.4 | 2.6 |
| 7.2 | 7.7 | 0.5 | 10.3 | 3.1 |
| 9.6 | 9.3 | –0.3 | 12.7 | 3.1 |
| 12.0 | 11.2 | –0.8 | 13.5 | 1.5 |
| 14.4 | 12.4 | –2.0 | 17.0 | 2.6 |
| 16.8 | 14.4 | –2.4 | 17.8 | 1.0 |
| 19.2 | 16.0 | –3.2 | 20.3 | 1.1 |
| 21.6 | 18.0 | –3.6 | 23.1 | 1.5 |
| 24.0 | 20.4 | –3.6 | 22.8 | –1.2 |
| 26.4 | 23.2 | –3.2 | 27.3 | 0.9 |
| 28.8 | 24.5 | –4.3 | 28.5 | –0.3 |

of 60 and 120 mm, respectively. In a comparison of the RMSE, the estimation accuracies improve from 4.94 to 2.54 mm at the depth of 60 mm, and 4.89 to 2.02 mm at the depth of 120 mm. They improve by approximately 49% and 59%, respectively, and the total estimation accuracy is improved by approximately 54%. Therefore, in the quantitative estimation of the air void thickness, better performance of reflectance analysis based on the bi-path model is confirmed.

However, one of the reasons for the quantitative estimation error is that the transmission coefficient of the microwave is not considered. To improve the estimation accuracy, it is necessary to examine the microwave propagation in more detail while considering the frequency dispersion characteristics of the microwave radiation, propagation, and scattering phenomena.

6. Conclusion

In this study, based on the microwave radar technique, nondestructive evaluation of air voids in concrete structures is examined. Through primitive experiments, we confirm that the amplitude of the reflected microwaves increases monotonically with the air void thickness, and the feasibility of quantitative air void thickness estimation is clarified. In order to discriminate the air void, we have analysed the phase shift of the reflected microwave using the time–frequency analysis approach. Second, we have introduced microwave reflection and refraction analysis on concrete–air–concrete layers based on the simple parallel incidence model, and a particular relation has been derived between the integrated reflectance and the air void thickness. Experimental evaluation results show that the discrimination of air voids based on the phase shift functions well, but the quantitative air void thickness estimation is not accurate from a practical perspective.

Additionally, we have introduced a sophisticated microwave propagation model, i.e. the bi-path model, which is based on ray-traced microwave propagation and provides a couple of propagation paths. In addition, the attenuation feature of microwaves is considered in the bi-path model. Consequently, the estimation accuracy is improved by approximately 54%, and the proposed evaluation method demonstrates the abilities of air void discrimination and quantitative thickness estimation.

In future studies, we will discuss a more precise microwave propagation analysis on each boundary. In particular, to conduct a more accurate estimation, it is necessary to consider a more rigorous propagation model in which the microwave propagation paths on the upper and lower boundaries of the air void are completely separated. In addition, it is necessary to consider the transmission coefficient of microwaves on each boundary. At the same time, the considerations of the frequency dispersion characteristics and microwave attenuation feature in the propagation media can also improve estimation accuracy of the air void thickness.

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