Depth super-resolved imaging of infrastructure defects using a terahertz-wave interferometer

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A B S T R A C T

We present a depth super-resolved 3D imaging method for inspection of defects in walls using terahertz swept-source optical coherence tomography. A depth profile analysis based on an annihilating filter method with noise reduction was applied for signal processing, and the results were compared with those of conventional inverse fast Fourier transform (IFFT) analysis. To evaluate the depth resolution, we measured a plastic step sample with 1 mm thickness, and its front and back surfaces were discriminated. This is corresponding to about 1/3 of the theoretical depth resolution of the conventional IFFT analysis. Moreover, we demonstrated 3D imaging of the void with a 10 mm width behind a ceramic tile and succeeded in reconstructing a significantly sharper cross-sectional void image than in the conventional analysis.

1. Introduction

Reconstruction of social infrastructure, such as tunnels, bridges, and roads, is challenging because of the substantial time and expense required. Maintenance of existing infrastructure is very important for long-term safety of use. In recent years, the deterioration of infrastructure has become a particularly serious problem because of the many years since construction, and accidents caused by exfoliation of infrastructure wall surfaces have been frequently reported in the media. Visual inspection and hammering tests are established as general inspection methods to prevent such accidents. However, these methods are challenging because of the lack of experts and difficulty of quantitative evaluation. Furthermore, these inspections contain a safety issue in that operation is required near their targets, which are often located several meters from the ground. Therefore, it is necessary to develop a new technique for contactless, nondestructive, and quantitative internal inspection of 3D structures.

Various methods have been proposed as next-generation infrastructure inspection techniques [1–4]. Terahertz (THz) waves are a promising form of sensing probe. THz waves are electromagnetic waves in the frequency range between microwave and infrared radiation. From an imaging perspective, they can be expected to provide a greater penetration depth than infrared radiation and a better spatial resolution than microwaves. Nondestructive inspection applications utilizing THz waves have been proposed in various fields, including dried foods [5], security [6], integrated circuit packages [7], and building insulation materials [8]. The inspection of infrastructure such as the coating of electric towers [9] and jacketed metal cables [10] has been examined. The feasibility of inspecting concrete and tiles using 2D imaging has also been demonstrated [11]. It is appropriate to select a THz source with a low-frequency band in the region of 100 GHz to obtain sufficient penetration depth in measurements of these construction materials, because of their thickness up to ~10 cm and their absorption of waves [12]. Fig. 1 shows a graph of the results investigated by the Japanese Ministry of Land, Infrastructure, Transport and Tourism into exfoliations that occurred between 2013 and 2014 [13], and depicts the relationship between the depth of exfoliation and the number of exfoliations. This result indicates that more than 90% of exfoliation is caused within 100 mm depth from the surface. On the other hand, the typical depth achieved by the conventional hammering tests is known to be up to 50 mm, and a depth greater than 50 mm is also acceptable for the actual application. It has been reported that THz waves can penetrate 100-mm-thick concrete [12]; thus, the nondestructive inspection of defects inside such infrastructures may be useful. In an actual inspection,
In this study, we demonstrate depth super-resolved 3D imaging of defects (voids) behind wall tiles using a THz–SS–OCT system, and discuss its potential for inspection applications. A frequency-tunable source in the range of 75–110 GHz and a Michelson interferometer were employed for THz–SS–OCT measurements. A depth super-resolution analysis (DSRA) based on an annihilating filter (AF) method with noise reduction [16,18,19] was applied as the signal-processing method to improve the depth resolution. The results were compared with those obtained using the conventional inverse fast Fourier transform (IFFT).

2. Configuration of the THz–SS–OCT system

We constructed a THz–SS–OCT system using a frequency-tunable source and a Michelson interferometer, as shown in Fig. 2. A frequency-multiplied continuous-wave source was used, with fundamental microwaves in the frequency range 12.5–18.3 GHz multiplied by six with an active frequency multiplier to generate a THz wave range of 75–110 GHz. Subsequently, the signal was output to free space from the horn antenna via an isolator. The frequency sweep was controlled by a PC via a General Purpose Interface Bus. The maximum output power of the source was approximately 100 mW. The emitted beam was split into two paths by a silicon beam splitter (resistivity: 8–12 kΩ cm, splitting ratio: 50/50), one of which irradiated the reference mirror, and the other of which irradiated the sample. The interferogram produced by these reflected and backscattered beams was detected using a calorimeter (PM4, Virginia Diodes Inc.) equipped with a horn antenna (75–110 GHz, WR10). The detected signals were fed to a PC through a data acquisition system. The sample was mounted on a three-axis motorized stage, and its scanning was controlled using a PC.

As shown in Fig. 2, in this paper the z-axis along the beam direction is referred to as ‘depth’, and the plane perpendicular to the z-axis as ‘lateral’. The x-axis of the plane is referred to as ‘vertical’, and the y-axis as ‘horizontal’.

3. Depth super-resolution analytical method

Early detection and repair of small defects can extend the lifetimes of structures, leading to a reduction in total cost. Hence, the depth resolution of the measurement system is one of the essential factors in the inspection of exfoliation.

In SS-OCT, the intensity profile in the depth direction is reconstructed through signal processing of the interferogram obtained by sweeping the source frequency (referred to as an ‘A-scan’). Conventionally, an inverse fast Fourier transform (IFFT) is applied for signal processing. Assuming that the frequency spectrum of the light source follows a Gaussian function, the depth resolution is determined by

$$\Delta z = \frac{2 \ln 2 \lambda_0^2}{\pi n \Delta \lambda}$$

(1)

where $\lambda_0$ is the center wavelength of the light source, $\Delta \lambda$ is the full width at half maximum (FWHM) bandwidth, and $n$ is the refractive index of the object. Thus, the depth resolution is determined by $\lambda_0$, $\Delta \lambda$, and $n$.

To improve this depth resolution, a DSRA [16] based on an AF method [18,19] was introduced. Two types of methods, a bandpass filter (BPF) and an iterative singular value decomposition (SVD), were used to reduce the noise contained in the measured interferograms. The BPF was used to reduce the periodic noise generated by multiple reflections, and the SVD was used to reduce the additive white Gaussian noise. The calculation method of SVD and determining the conditions (number of decomposing elements, number of remaining elements, and threshold for ceasing iterations) was used on the methods in Ref. [16]. These noise reduction methods can be expected to improve the evaluation performance of the AF method for data analysis with high-level noise. The AF
method is generally used to reconstruct a sparse signal such as an impulsive train, and is effective in retrieving the original signal from a small quantity of measurement data. Assuming that the number of boundaries of the object is known, the depth information is retrieved using the AF method in the SS-OCT analysis. When a multilayered object is known, the depth information is retrieved from the measured interferogram is modeled as

\[ D_{a} = \sum_{l=1}^{L} \left( A_{l}^{p} + A_{l}^{*} \gamma_{l}^{2} \right), \]  

(2)

\[ A_{l} = \Delta k L \left( 2 \theta_{b} - \theta_{a} \right), \]  

(3)

\[ \gamma_{l} = e^{2 \theta_{b} \Delta k}, \]  

(4)

where \( \theta_{a} = (n_{l} - n_{0})/(n_{l} + n_{0}) \) is the reflection coefficient of the lth boundary, \( b_{l} = \sum_{p=1}^{l} (\theta_{p} - \theta_{p-1}) \theta_{p} \) is proportional to the optical path length up to the lth boundary, \( z_{p} \) is the geometric length, \( n_{l} \) is the refractive index, \( L \) is the number of boundaries, \( \kappa_{\text{min}} \) is the minimum wavenumber of the light source, \( \Delta k \) is the step size of the wavenumber, and \( s = 0, 1, 2, \ldots, K - 1 \) is the index of the wavenumber. Then, the attenuation in the object and multiple reflections are assumed to be negligible.

When the 2L solutions of a polynomial \( P \) with complex variable \( t \) are \( \gamma_{l} \) and \( \gamma_{l}^{*} \), the polynomial \( P(t) \) is typically written by

\[ P(t) = \prod_{l=1}^{L} (t - \gamma_{l})(t - \gamma_{l}^{*}) = \sum_{p=0}^{2L} p_{l} t^{l}. \]  

(5)

When the solutions of \( P(t) \) are equal to \( \gamma_{l} \) and \( \gamma_{l}^{*} \) of the interferogram \( D_{a} \), the convolution of the coefficients \( p_{l} \) (also known as the ‘annihilating filter’) with \( D_{a} \) of Eqs. (2)–(4) is zero using Eq. (5), i.e.,

\[ \sum_{l=0}^{2L} p_{l} D_{a-l} = \sum_{l=1}^{L} \left\{ A_{l}^{p} \left( \sum_{p=0}^{2L} p_{l} \gamma_{l}^{2} \right) + A_{l}^{*} \gamma_{l}^{2} \left( \sum_{p=0}^{2L} p_{l} \gamma_{l}^{*} \right) \right\} = 0, \]  

(6)

\[ k = 0, 1, 2, \ldots, K - 1. \]

Here, \( p_{l} \) is obtained from \( D_{a} \) by solving Eq. (6). Subsequently, \( \gamma_{l} \) and \( \gamma_{l}^{*} \) are obtained from \( p_{l} \) by solving Eq. (5). \( b_{l} \) is obtained from argument \( \phi_{l} \) of complex number \( \gamma_{l} \) using the following equation:

\[ b_{l} = \frac{\phi_{l}}{2 \Delta k}. \]  

(7)

\( A_{l} \) and \( A_{l}^{*} \) are given by solving the linear least-squares problem for the signal model and the measured interferogram. The interferogram of each boundary is reconstructed from the obtained parameters \( A_{l}, A_{l}^{*}, \gamma_{l}, \) and \( \gamma_{l}^{*} \), and the amplitude value at the center frequency is obtained.

4. Experiments

4.1. System performance

The lateral spatial resolution, depth resolution, and depth of focus (DOF) of the constructed THz-SS-OCT system near the sample were evaluated. These are important parameters that determine the imaging characteristics of the system.

We measured the change in beam size along the depth direction using the knife-edge method to evaluate the lateral resolution and DOF. The detector and lens were placed behind the knife of a cutter, and the transmitted beam was detected by the detector. The output power of the source was set at 92.5 GHz, which is the central frequency of the source. The knife was moved by 60 mm, and intensity data were acquired at 0.1 mm intervals. The horizontal and vertical beam profiles near the focal position are shown in Fig. 3a. The dotted lines denote the differential data obtained from the raw measured data. The beam diameter (FWHM) was determined by fitting these beam profiles with a Gaussian function, giving horizontal and vertical diameters of 6.3 mm and 7.0 mm, respectively. Fig. 3b shows the beam diameter in the depth direction at 1 mm intervals in the horizontal and vertical directions. The DOF was determined by fitting the measured values, depicted as dotted

![Fig. 3](image-url)
lines in Fig. 3b, with a hyperbolic function. The DOFs obtained in the horizontal and vertical directions were 81.9 mm and 98.6 mm, respectively.

To confirm the depth resolution by conventional Fourier analysis, the plane mirror was measured as an object. In the A-scan measurement, the interferogram was obtained by acquiring the intensity when the frequency was swept in the range of 75–110 GHz at intervals of approximately 60 MHz. The frequency sweep was performed in approximately 120 s. The same sweep conditions were also used for A-scans in other experiments. The plane mirror of the object was moved within a range of ±50 mm near the focal point at 5 mm intervals, and the measurement was repeated ten times at each position. For preprocessing, the intensity profiles in the depth direction were reconstructed by IFFT. By fitting each reconstructed depth profile with a Gaussian function, the depth resolution (FWHM) was obtained. Fig. 4a shows the result of the fitting and measured depth profiles when the plane mirror is located near the focal position, and measured values with a shape close to a Gaussian function were obtained. The average value and standard deviation of the depth resolution obtained from all fitting results was 7.65 ± 0.02 mm, which is close to the theoretical value of 7.49 mm. Fig. 4b shows the depth profile without apodization (boxcar apodization), and the depth resolution was 5.09 ± 0.03 mm. In this case, a higher resolution could be obtained, but the side lobes of the depth profile were increased. Fig. 5 shows the relationship between the average values of the peak positions fitted with a Gaussian function and the actual displacements of the plane mirror of the object, from which an almost linear characteristic with a gain error of 0.19% was obtained.

To evaluate the depth resolution by DSRA, a plastic sample with a step structure, as shown in Fig. 6 was used as an object. There were five designed values of step thickness at 1, 2, 3, 5, and 10 mm, and the material used was high-density polyethylene (HDPE; density: 0.96 g/cm³). The actual thickness of each step as a reference was measured in a range of 80 mm × 180 mm in 5 mm intervals near the steps of the sample using a coordinate-measuring machine (CMM; CRISTA-Apex S574, Mitutoyo Corp.) of contact-probe type. Fig. 7 shows the measured shape of the sample. The average values and standard deviations of the thickness of each step were 0.88 ± 0.03, 1.89 ± 0.03, 2.86 ± 0.02, 4.82 ± 0.01, and 9.91 ± 0.04 mm, respectively. The refractive index of the sample was calculated from the actual thickness of 9.91 mm measured by the CMM and the optical thickness of 15.3 mm obtained by the A-scan of the step, giving n = 1.54. This result is consistent with previous reports [22,23]. In this case, the depth resolution by IFFT analysis with boxcar apodization is 3.29 mm in the sample.

A-scan measurements were repeated ten times near the center of each step of the sample using our THz-SS-OCT system. To reduce the noise in the obtained interferograms, the two types of noise reduction processing described in Section 3 were performed. The passing depth range of the applied BPF was 320–538 mm near the sample position. The SVD conditions were as follows: the number of decomposing elements to be 200, the number of remaining elements to be 4, which is twice the sample boundary, and the threshold for ceasing iterations to be $1 \times 10^{-8}$.

Fig. 8 shows the results of the comparison between the interferograms before and after noise reduction processing. The beat signal was clearly extracted by the noise reduction processing. When the front and back surfaces are adjacent, the periods of each interferogram generated by their reflections are very close. As a result, a beat signal is generated. These noise-reduced interferograms were converted into depth profiles by the AF method with an assumed number of boundaries of two, and the result was then compared with the depth profiles converted by IFFT analysis with boxcar apodization (Fig. 9). As a result, the 1 mm thick front and back surfaces of the sample were resolved. This resolution is
approximately 1/3 that of conventional IFFT analysis. Using IFFT, two peaks could be confirmed as if a thickness of 3 mm or less could be resolved, despite the resolution of IFFT analysis being 3.29 mm. This phenomenon is caused by fringe patterns that occur in the super-resolution region \[24\]. To confirm this, the thickness was calculated from the difference between the two peaks of the front and back surfaces and compared with the actual thickness measured by the CMM. Fig. 10 shows the comparison of the evaluated thicknesses. The values obtained by IFFT remained almost constant below 3 mm. In contrast, the values obtained by DSRA changed according to the actual sample thickness,
even below 3 mm. Therefore, it was confirmed that the DSRA was able to measure the thickness more accurately than the IFFT analysis. However, focusing on the residual from the thickness measured by the CMM, an average error of 0.51 mm occurred at a thickness of 1 mm. This discrepancy was observed in the samples with thicknesses of 1, 2, and 3 mm. One possible reason for this difference is the systematic error due to the bent surface of the sample, as shown in Fig. 7, causing oblique incidence of the beam onto the surface. Although the systematic error is approximately 0.5 mm, a smaller depth difference of 0.4 mm was clearly observed in the DSRA, as shown later. This means that even if the systematic error is greater than the local depth difference, the relative uncertainty of the depth is smaller than the systematic one. To evaluate the relative uncertainty, the repeatability of the peak positions was evaluated. The root mean square (RMS) of the measured thickness of 1 mm was then determined as 20 μm corresponding to a FWHM of 46 μm (= 2RMS/2 ln 2). This value indicates that the potential relative depth resolution of the DSRA method is approximately 70 times better than that of conventional IFFT analysis.

4.2. 3D imaging of void

4.2.1. Sample and measurement conditions

We performed 3D imaging of voids to demonstrate the effectiveness of our THz–SS–OCT system for internal inspection of walls. The prepared sample has a multilayer structure composed of a ceramic tile and two mortar plates placed behind it, as shown in Fig. 11. The thicknesses of the tile and mortar plates were 8 mm and 10 mm, respectively. Both materials conformed to Japanese industrial standards (ceramic tile: JIS A 5209, mortar: JIS R 5201), and the tile in particular has previously been used commercially in actual infrastructure. Behind the tile, the void (air gap) was arranged at 10 mm depth with a 10 mm gap as a pseudo defect. The sample was fixed on a motorized stage, and a 60 mm × 30 mm area near the center was scanned at 2 mm intervals (31 × 16 = 496 pixels). At each position, an interferogram was obtained by sweeping the frequency of the source in the range 75–110 GHz with a frequency interval of approximately 60 MHz. The acquired interferogram was converted into an intensity profile in the depth direction using IFFT and DSRA, and their results were compared. As a pre-processing step of IFFT, the interferogram was apodized by a Gaussian function. The number of data was then increased to 1250 by zero filling to reconstruct a 3D image with approximately equal data intervals in the horizontal and depth directions. In the noise reduction processing of the DSRA, the passing depth range was 320–538 mm as the condition of the BPF. The SVD had 200 decomposing elements, 8 remaining elements, and an iteration threshold of 1 × 10⁻⁸. Five boundaries were assumed in the AF method. The DSRA image was rounded to data intervals of approximately 2 mm in depth at the time of image reconstruction for comparison with the IFFT image.

4.2.2. Results of 3D imaging

Fig. 12a and b shows the 3D images of the sample reconstructed by...
IFFT and DSRA, respectively. In these figures, the lateral direction is given by their geometric distances, and the depth direction is drawn in the optical path difference (OPD). Fig. 13a and b shows the cross-sectional (referred to as ‘B-scan’) images on the red-colored $y-z$ planes in Fig. 12a and b, respectively. Comparing Fig. 13a and b, the image becomes much sharper in DSRA than in IFFT. The void width in the depth direction between the tile and mortar was calculated from the results of the DSRA. As a result, the void width was evaluated as 9.80 ± 0.04 mm, in good agreement with the arranged width of 10 mm. Therefore, it was confirmed that DSRA works validly even for building materials with large attenuation. However, there was a slight difference between the left and right sides of the reflection position of the mortar back surface, indicated by the yellow arrows in Fig. 13b. This may be caused by differences in the refractive index and the actual thickness of the mortar.

Fig. 14a–d shows slice (referred to as ‘C-scan’) images on the $x-y$ plane of the tile front surface, tile back surface, mortar front surface, and mortar back surface extracted from Fig. 12a, respectively. In addition, Fig. 14e–h shows photographs of their exterior. Fig. 15a–d shows C-scan images extracted from Fig. 12b at the same positions as in Fig. 14a–d, and Fig. 15e–g shows C-scan images at −2 mm position in the depth direction from Fig. 15b–d, respectively. Because the front surface of the
tile is smooth and flat, the intensity distributions in Figs. 14a and 15a are both almost constant. In contrast, the intensity distribution in Fig. 14b has a striped pattern due to the uneven structure of 0.4 mm on the back surface of the tile. In Fig. 15b and e reconstructed by DSRA, this uneven structure is resolved in the depth direction by the improved resolution. Focusing on the C-scan images of the front (Fig. 14c) and the back (Fig. 14d) surfaces of the mortar reconstructed by IFFT, the lateral 10 mm void between the mortar plates is clearly visualized. The C-scan images reconstructed by DSRA (Fig. 15c, d, 15f, and 15g) are separated in the depth direction, even though the mortar surface was nearly flat. This separation may be an effect of the structure on the back surface of the tile located on the front side of the mortar. Fig. 15 shows a summed image of Fig. 15c and f, which is very similar to the IFFT image in Fig. 14c. The void width was calculated from the difference between the positions where the maximum and minimum intensity slope in the horizontal direction in the summed data. The calculated void width was 10.8 ± 1.0 mm, consistent with the arranged width of 10 mm. Thus, we succeeded in obtaining images that reflect the geometric shape of each boundary using depth super-resolved 3D imaging.

The current measurement time for a single A-scan was approximately 120 s, and the time taken for the 2D scan (16 × 31 = 496 pixels) to obtain the 3D image was approximately 16.5 h. Shortening the measurement time is an important issue for practical inspections. One of the reasons for this is the slow time response (~0.1 s) of the calorimeter employed as a detector. For example, a Schottky barrier diode detector with a sufficiently fast response time of several tens of picoseconds could be employed as the detector [25,26]. In addition, a fast-sweeping synthesizer of 50 μs [27] and frequency multipliers could be adopted instead of a signal generator. A significant improvement in the measurement time would be expected as a result of these changes of devices. The measurement time for the same 2D scan would be reduced to approximately 24 ms (50 μs × 496 pixels) if the stage drive time was ignored.

In this paper, comparatively thin samples were measured. On the other hand, in actual measurement, a measurement of thicker samples may be required as mentioned in Section 1. In this case, it is necessary to improve the SNR of the measurement system. The dominant noise factors are unwanted reflections and their multiple reflections in the optical system. By replacing a part of the optical path with a waveguide and using an isolator, it can be expected to reduce these noises.
5. Conclusion

We constructed a THz-SS–OCT system using a frequency-tunable source in the range of 75–110 GHz for internal inspection of defects in walls. We applied a DSRA based on an AF method for signal processing. To evaluate the depth resolution, we measured a plastic step sample with 1 mm thickness, and its front and back surfaces were resolved. This result confirms to approximately 1/3 of the depth resolution of conventional IFFT analysis. In addition, the repeatability of the thickness measurement was derived to evaluate the potential depth resolution of the method as 46 μm at FWHM. Furthermore, we performed 3D imaging of a void 10 mm in width on the back side of a ceramic tile, and we obtained an image of the uneven structure of 0.4 mm on the back surface of the tile, demonstrating a potential depth resolution better than 1 mm. Thus, depth super-resolved imaging by THz-SS–OCT is shown to be effective in obtaining detailed defect conditions of walls. In future studies, it will be necessary to consider the construction of a portable THz-SS–OCT system for on-site infrastructure inspection, and to improve the measurement time.

Author Statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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