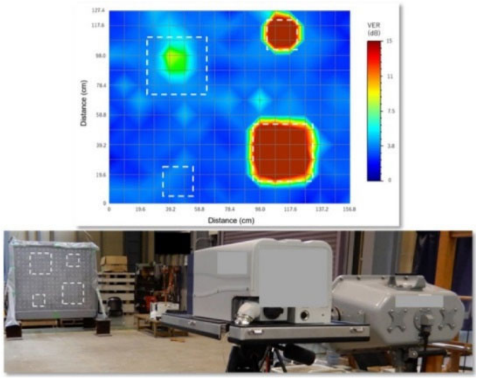
Visualization Technology for Internal Defects in Refractory Walls of Furnace Plants Using Non-Contact Acoustic Inspection Method



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Conventionally in waste incineration facilities, the integrity of refractory walls of the boiler furnace is checked visually and/or by tapping. Tap inspection is widely applied because of its simplicity involving only hammer tapping and listening to the sound that is made. However, tap inspection also has problems in the case of the inspection area being of a great height and/or covering a large area, such as temporary scaffolding being expensive and criteria of inspection and interpretation of the results depending on individual inspectors. These issues are expected to be solved by Non-Contact Acoustic Inspection (NCAI). So, Mitsubishi Heavy Industries, Ltd. (MHI), together with Toin University of Yokohama, trialed the use of NCAI for refractory wall inspections and assessed its performance in terms of identification of internal defects in test pieces into which simulated defects had been added. The results show that a 200-mm-square defect, which is the identifiable minimum defect size by the conventional tap inspection method, can be visualized and identified by the NCAI method from a distance of 10 m.

1. Introduction

In recent years, concrete public infrastructures such as tunnels and bridges, which were built during Japan's rapid economic growth, have been reaching the end of their service life. As these concrete structures age, peeling and flaking occur, causing an increasing number of serious incidents. Therefore, defect inspection technology to maintain/manage such infrastructures is receiving wide public recognition for its importance. However, while inspected visually in most cases, voids and internal cracks, which will cause concrete to peel and flake off, can be detected only when they develop into surface deformation such as cracking and peeling. It is also difficult to visually evaluate how far defects extend below the surface. Therefore, the internal defects, which are a predictor of peeling and flaking, are traditionally inspected by tapping as well.

In the tapping method, a hammer is used to tap on the surface of the inspection object, and whether there is a defect, is determined based on the difference in the sound that is heard. However, this method relies on the experience and capabilities of individual inspectors. When the inspection area is located high up and/or is large, temporary scaffolding or an aerial work platform needs to be arranged in addition to regulate the surrounding area to ensure safety. As the interpretation of the inspection results is dependent on the individual, it is also difficult to retain objectivity in inspection quality. Technological development has been actively carried out under such circumstances to solve these individual problems of tapping test. However, because many of these technologies are premised on the precondition of their operations in contact with or in close proximity to the inspection object, real improvements have not actually been made in this regard(1).

Among MHI Group's product portfolio, furnace refractory wall inspection at facilities such

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as waste incineration plants has the same issue as these concrete infrastructures. If refractory materials flake off from the wall while the plant is in operation and the water cooling tube in the wall gets exposed, it is considered that such exposure to high temperature leads to corrosion damage. It is also conceivable that a large amount of refractory materials falling from a considerable height and directly hitting/damaging the furnace facility will result in suspension of operations. To prevent this, the integrity of refractory walls is checked regularly, as shown in **Figure 1**.

In the future, if the progression of wall degradation becomes assessable quantitatively by inspection that is quick and accurate, such inspection results will enable us to properly plan repair work. This will make it possible to conduct periodic inspections in an efficient manner (shorter inspection period and lower cost) from the viewpoints of preventive maintenance and planned repair. The NCAI method is expected to be able to solve the problems related to inspection efficiency and quality records, which have been difficult with the tap inspection. This report presents NCAI measurement technology and the results of internal defect measurement using refractory test piece.

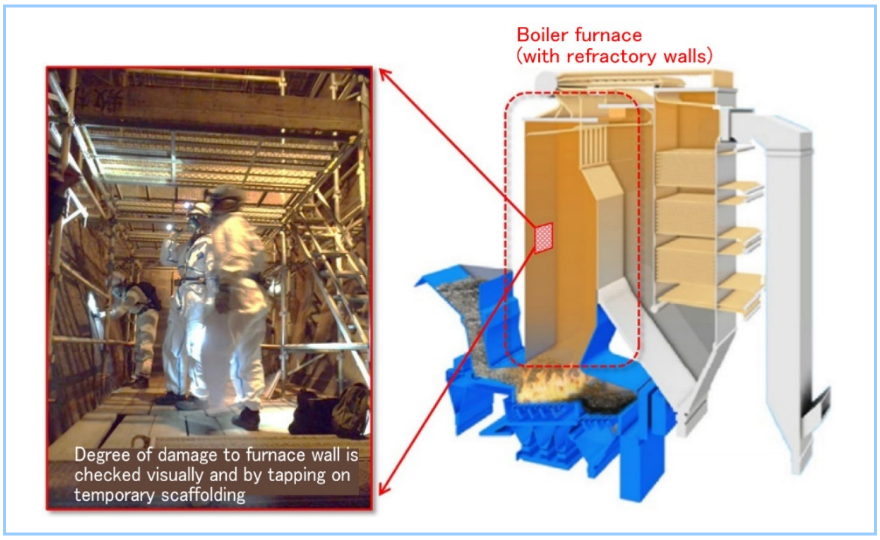


Figure 1 Inspection underway for refractory walls of stoker furnace at waste incineration plant
Images from website of MHI Environmental & Chemical Engineering Co., Ltd.

2. NCAI measurement mechanism ("inspect from afar" rather than "listen closely")

In the NCAI method, the mechanism for generating the difference in the sound between the defective part (with peeling and voids) and the integrity part is the same as that of the conventional tapping method. However, as an alternative to hammer tapping, the NCAI method uses aerial acoustic waves from a speaker to vibrate the surface of the inspection object. If there is a defect directly below the vibrating surface, the part immediately above the defect has a lower flexural rigidity than the integrity part. Flexural vibration is therefore likely to occur in this defective part.

Figure 2 shows the measurement mechanism in the NCAI method. Suppose there is a defect with a size of "a" at a depth of "h" from the surface. The flexural vibration of this part is a resonance at the primary natural frequency (resonance frequency) as considered in the resonance model for a simply supported beam structure at both ends. The defective part can be distinguished from the remaining intact part based on the differences in the resonance frequency distribution. While also depending on the type of materials to be inspected (each with a different Young's modulus, Poisson's ratio and density), the flexural resonance frequency of a defective part in the same material is proportional to the depth of the defect and its planar area size.

In the tapping method, the sound generated by the vibration of the surface immediately above a defect slightly differs from the integrity part. The inspector listens and makes out this slight difference. In the NCAI method, on the other hand, the vibration of the surface immediately above a defect is directly measured by the laser doppler vibrometer, whereby the difference from the integrity part is visualized quantitatively in terms of vibrational energy. The NCAI method therefore uses acoustic waves from a speaker instead of a hammer, and laser beams from the laser doppler vibrometer instead of listening to the sound. These means of non-contact measurement have enabled non-destructive inspection from afar.

However, because of their varying shapes, the actual defects formed in structures show frequency spectra with complicated resonance peaks. It is therefore not practical to obtain each of the multiple peaks of characteristic frequency for an unknown defect at every measurement. These problems have been solved by irradiating the inspection object in advance with acoustic waves with resonant frequency bands corresponding to defects with certain depths and sizes to vibrate the surface, and focusing on the vibrational energy difference from the integrity part. Moreover, the inspection surface is scanned with a laser beam to measure vibrational energy at each point of the inspection area, identifying a spread of the defective part as a two-dimensional distribution of relatively high vibrational energy levels. Serving as a baseline, the integrity part is known to have vibrational energy whose level is lower in certain ranges in all the frequency bands than the defective part[2].

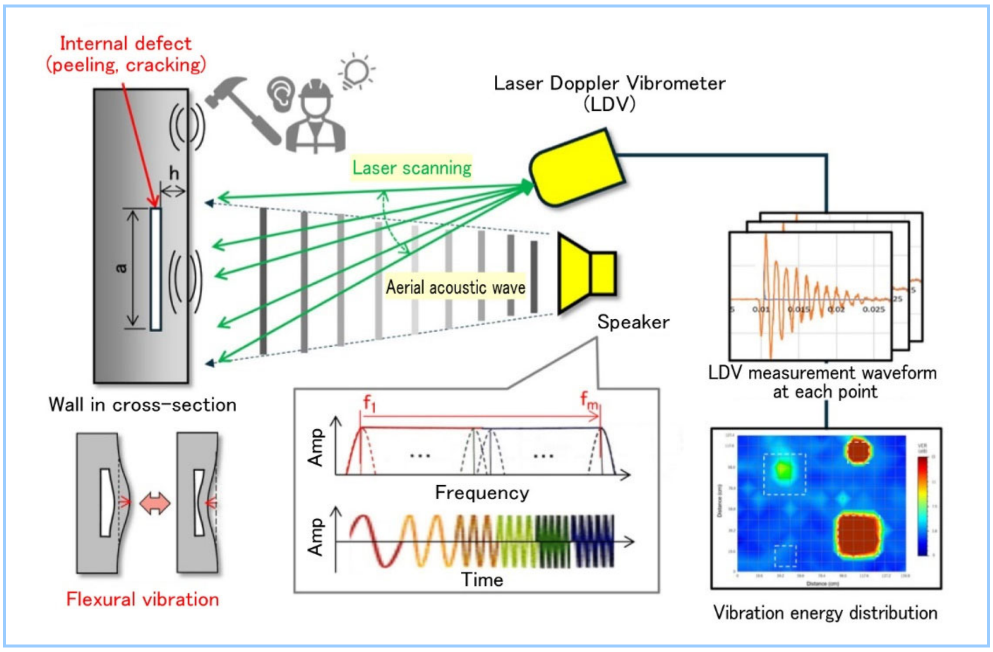


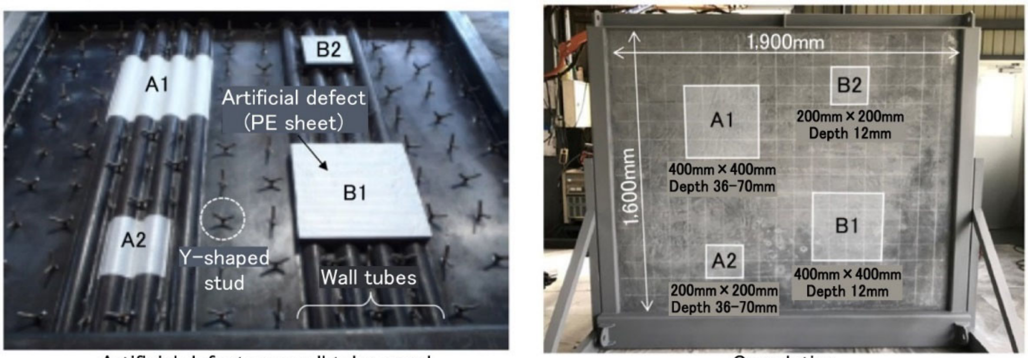
Figure 2 Measurement mechanism of Non-Contact Acoustic Inspection (NCAI) method (in comparison with manual hammer tapping)

3. Test pieces with simulated defects and internal defect measurement test results

3.1 Artificial defect-embedded test pieces with simulated refractory boiler wall structure with wall tubes

Figure 3 shows a refractory wall test piece with artificial defects, simulating the internal structure of a boiler furnace wall in general. This test piece is 1,600 mm length and 1,900 mm wide, with a 70-mm-thick SiC castable refractory material mounted onto a wall tube panel. The internal structure consists of multiple Y-shaped studs, wall tubes, and four artificial defects of simulated peeling.

As shown in the figure, artificial defects are fabricated by placing a 1-mm-thick polyethylene sheet in the predetermined positions before pouring a refractory material into the panel and letting it naturally dry and settle. The specifications of artificial defects are defined by two parameters, i.e., the depth from the surface and the size of the planar area. Supposing the occurrence of flaking due to anchor bolt corrosion, two depth levels from the surface were arranged: Type A (36 mm to 70 mm) along the curves of tubes, and Type B (12 mm, flat) over the top of Y-shaped studs. For the planar area, two sizes were prepared: Type 1 (400 mm square) and Type 2 (200 mm square). These are the typical sizes that are normally identifiable by inspectors. In total, there are four types of arrangements (A1, A2, B1 and B2).



Artificial defects on wall tube panel (before refractory material is constructed) | Completion (after refractory material is constructed)

Figure 3 Artificial defect-embedded test piece with simulated refractory structure with boiler wall tubes

3.2 Performance comparison with tapping inspection

To determine the acoustic excitation frequency conditions for the NCAI method, the surface vibration characteristics of each of the defective parts and the integrity part were measured. The excitation force of a hammer was used as the input response, while the surface vibration by the laser doppler vibrometer was used as the output response. Based on their ratio, the flexural vibration characteristics were compared between the integrity part and the defective parts. **Figure 4** shows the results.

Consequently, a significant amplitude difference was confirmed between the integrity part and the defective parts in the band of 500 Hz to 4,000 Hz. Based on the results, multi-tone frequency acoustic waveforms in the flexural vibration band with the depth and size of these measured defects were created. With the test placement shown in **Figure 5**, the acoustic wave was irradiated from the speaker to the test piece that was located 5 m away, facing the speaker. Simultaneously, the laser doppler vibrometer was used to scan the surface of the test piece with a laser beam. The surface area, which is 1,400 mm length and 1,700 mm wide, was divided by a 100 mm by 100 mm grid, thus producing a total of 238 measurement points (14 pts by 17 pts). The vibrational energy in the frequency band at each measurement point was visualized as a two-dimensional distribution.

Figure 5 compares the results between the NCAI measurement and the hammer tapping by an inspector with 20 years of experience. The inspector using the conventional method could detect shallow defects B1 and B2, but not deep defects A1 and A2. On the other hand, the NCAI method showed, for B1 and B2, a vibrational energy difference of 15 dB relative to the surrounding integrity part, allowing them to be identified. Even a deep defect of A1 (400 mm square), which the inspector was unable to detect, had a vibrational energy difference of 6-8 dB, leading to successful identification.

Although the location of defect A1 was successfully indicated by the NCAI method, the identified size was smaller than the actual one, showing only a part of the entire defective area. This is presumably attributed to its three-dimensional shape. Unlike defects B1 and B2, which are in the shape of a plane parallel to the surface, Type A defects are three-dimensional along the curves of tubes in the test piece with varying depths at each measurement point. This makes the measurement conditions more complex than simply uniformed flexural vibration characteristics. With regard to defect A2, the NCAI method also failed to detect this, as was the case with the inspector using the conventional method. In conclusion, the defective parts were able to be identified by a signal level difference of 3 dB or more, which is significant in measurement and serves as an indication for distinguishing a defective part from an integrity part. It has been demonstrated that the NCAI method can identify internal defects without contact as effectively as or better than the tap inspection by the inspector.

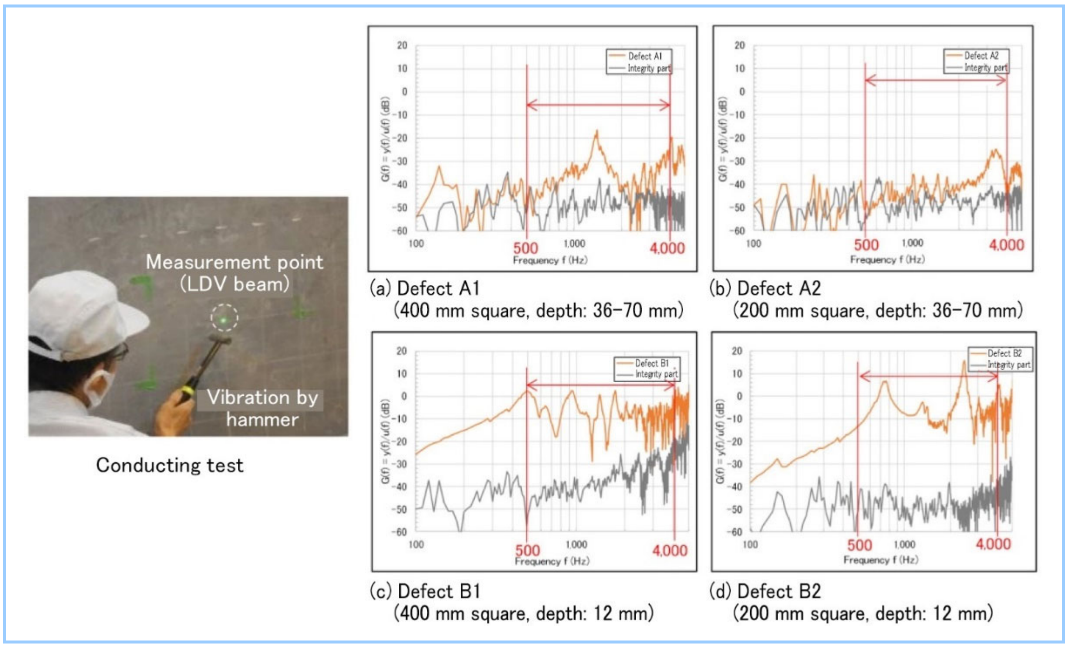


Figure 4 Comparison of flexural vibration characteristics between each of defective parts and integrity part

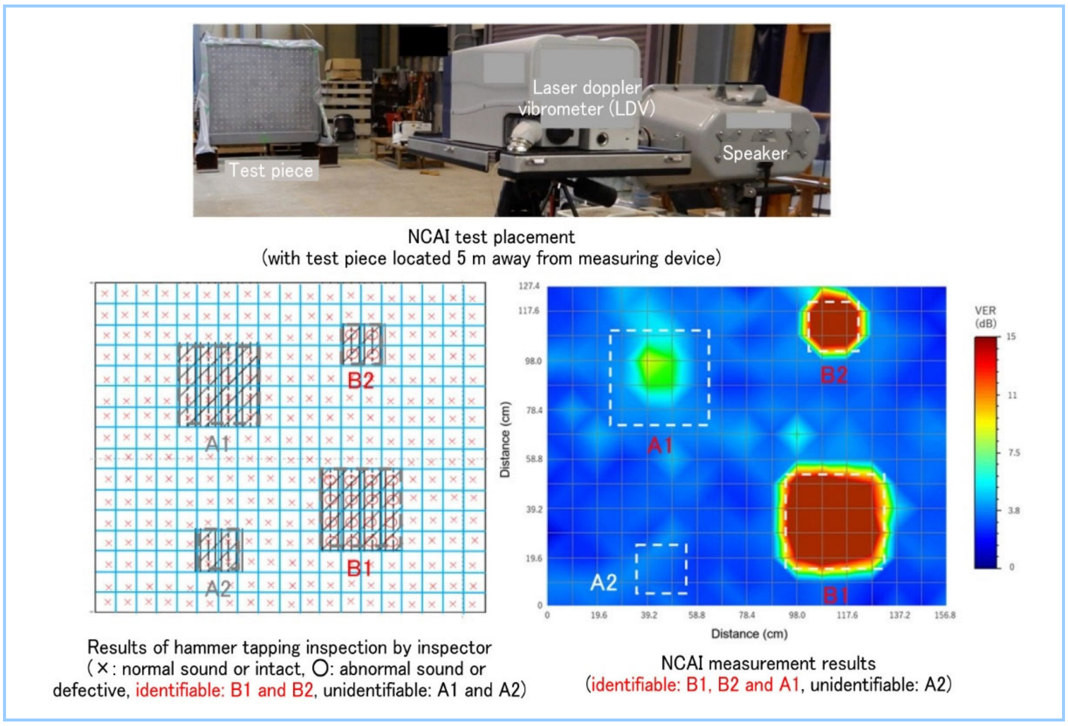


Figure 5 NCAI test placement and comparison of its defect identification results with hammer tapping method

4. Measurement performance assessment for use in inspection at great height or of wide area

In this study, the NCAI method is intended to be practically used for the waste incinerator shown in Figure 1. Considering its structure and size, the robustness was evaluated to show the impact of the applied attitude angle and straight-line distance between the measuring device and the inspection surface on the measurement performance.

Starting from the test piece's position being 5 m away facing the measuring device (θ = 0°, as shown in Figure 5), the angle was changed from 30° to 45° to 60°. The measurement results are compared in **Figure 6** (a) to (c). Up until 45°, defects B1 and B2 can be distinguished from the surrounding integrity part. Reaching 60°, however, the borderline between the integrity part and the defective parts becomes unclear. Defect A1 becomes unidentifiable at 45°. This is believed to be caused by varying phases at each measurement point with the incident angle of the excitation acoustic wave front. The multiple vibrational modes at the surface then become excited, allowing them to influence each other.

Figure 7 shows the measurement results of the test piece being located at a maximum straight-line distance of 10 m from the measuring device. When compared with Figure 5 in which the test piece is 5 m away, the difference in vibrational energy between defect A1 and the surrounding integrity part is relatively lower, making the identification difficult. However, defects B1 and B2 are clearly identified, indicating the defect identification performance that is comparable to the inspector. These demonstration test results show the possibility of simultaneously inspecting an area with a maximum size of about 14 m square from same place, if the distance is 5 m to 10 m and the viewing angle within the range of ±45°.

Measurement of the actual unit is expected to be conducted in an enclosed space. Therefore, as the NCAI method uses acoustic waves from the speaker to irradiate the inspection object and vibrate its surface, the sounds generated other than for this purpose are those directly reflected from the inspection surface and reverberations from the surroundings such as the floor surfaces and walls. These reverberations are expected to cause disturbance vibrations of the laser doppler vibrometer itself, increasing the internal measurement noise and decreasing the measurement performance. It will therefore become necessary to make the laser doppler vibrometer soundproof and vibration-proof for enhanced robustness in defect identification during practical use.

In regard to the inspection of refractory wall integrity, **Table 1** compares the conventional tapping method and the NCAI method. As mentioned earlier, the tapping method requires the installation of temporary scaffolding every time the inspection is conducted, while the NCAI method can basically be done without it. In the tapping method, the inspectors move around the inspection area while conducting the inspection, and have to make on-site judgement regarding defects to record the result using a “○” or “×” (with photographs in which the defect’s location is marked). In the NCAI method, on the other hand, the results for defects can be stored as digital data (i.e., visualized images). Therefore, the data can be used after the inspection to re-examine the inspection results. Enabling a certain level of quality to be assured based on the objective criteria is also advantageous.

From the results described above, additional work entailing the wall integrity inspection can be minimized if this technology is applied, and the inspection efficiency can be expected to improve. In this measurement method, based on digitally recorded results, a credible decision can be made regarding whether repair is required. Based on that decision, the next inspection and repair work can then be planned properly.

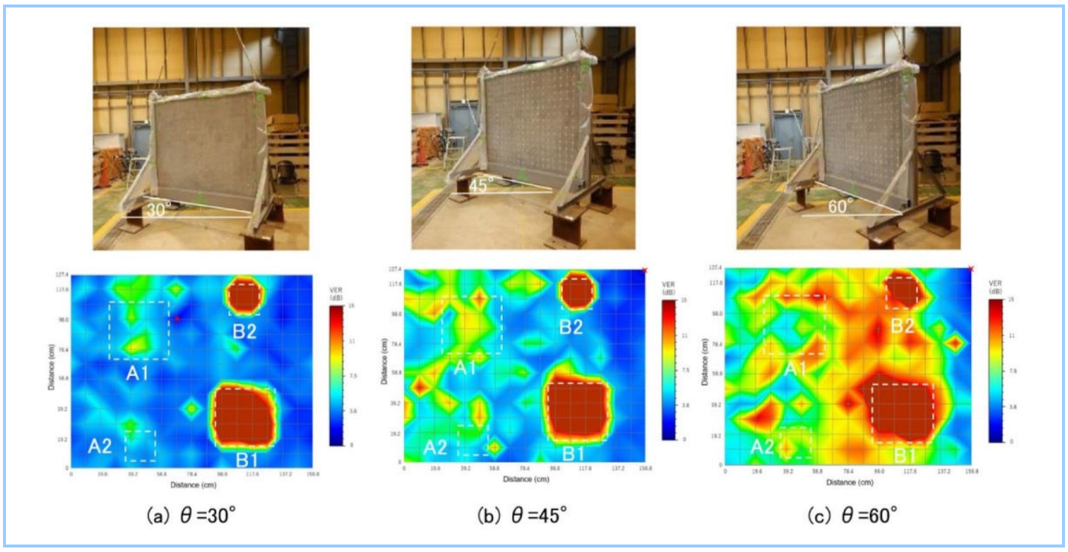
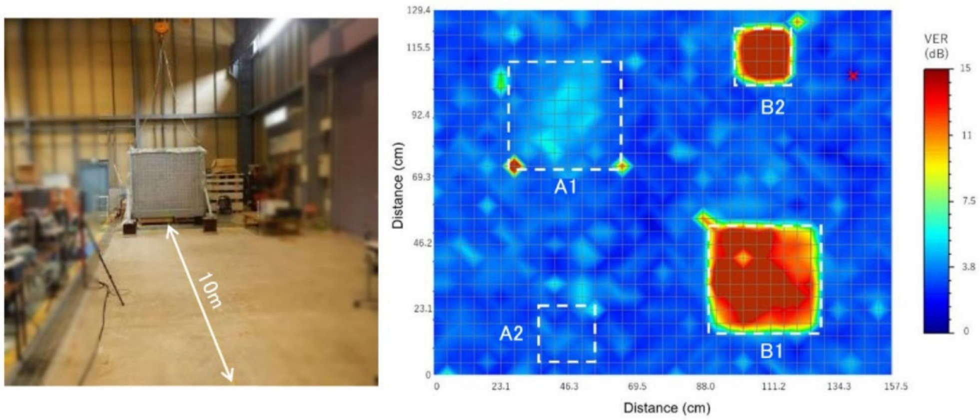


Figure 6　NCAI method’s dependence on measurement angle (upper: position of test piece, and lower: measurement results)



View of test piece 10 m away from measuring device

Measurement results of NCAI method (a 50 mm × 50 mm grid, 35 pts × 29 pts = 1,015 pts)

Figure 7　Measurement results of NCAI method with test piece at distance of 10 m

Table 1　Comparison of conventional method and NCAI method

Item	Conventional method (by tapping)	NCAI method
Temporary scaffolding	Required for all inspection parts	Basically no need (footing enough for manual work)
Inspection area	Inspected within movable range of inspector (according to predetermined measurement points)	About 10-m-square area is inspected simultaneously from point where measuring device is set up
Defect identification performance	Dependent on inspector's capabilities	Comparable or superior to experienced inspector (with reproducibility)
Inspection (quality) records	Judged by "○" or "×" Analog	Quantitative records Digital

5. Conclusion

In this report, the NCAI method, which can replace a conventional tapping inspection, is presented to customers and service sites who are faced with issues related to the inspection of MHI's large structural products for internal defects or their screening. This measurement technology was tested and verified, supposing its application in the periodic inspection on the integrity of refractory walls of a waste incineration boiler. The results show that, with this completely non-contact method of NCAI, an area about 10 m square can be simultaneously inspected at defect identification performance levels that are comparable or superior to a tapping inspection. Looking forward, we will solve the issues in the application to the actual unit for each need, aiming to improve the efficiency of inspection services and plant reliability.

References

(1) Tsuneyoshi Sugimoto, et al., Non-contact and Non-destructive Inspection Method for Civil Engineering Structure By Acoustic Irradiation-Induced Vibration and Laser Doppler Vibrometer (Part1), Inspection Engineering, 2017.8 p.7～17

(2) Tsuneyoshi Sugimoto, High Speed Non-contact Acoustic Inspection Method by Acoustic Irradiation Induced Vibration for Infrastructure Inspection, Ultrasonic Technology 2019.11-12　p.92～96