TOFD-TFM Ultrasonic Imaging System for Damage Quantification to Help Achieve Practical, Stable Operation of Power Plant Piping Systems

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Stable and economical operation of power plants requires an accurate understanding of facility conditions and appropriate maintenance. In recent years, the operating conditions of power plants have been getting difficult, because of the fuel transition toward decarbonization and the need for flexibility in the operating load to balance renewable energy fluctuations. This raises concerns about the progression of any new damage. Although the technology to quantify the height of a discontinuity (i.e., a flaw) in a non-destructive manner is pivotal to assessing the strength and remaining life of a structure, it was very demanding in terms of measurement skills and accuracy. This was a bottleneck in maintenance planning. Mitsubishi Heavy Industries, Ltd. has therefore combined Time of Flight Diffraction (hereinafter referred to as TOFD) for robust assessment of flaw height with Total Focusing Method (hereinafter referred to as TFM), which is a multi-channel signal and image processing technology, to create the TOFD-TFM ultrasonic imaging system for flaw height quantification. While currently being used to measure the heights of flaws, the system is also being used to perform a temporal assessment based on the obtained data, thereby helping to make a practical maintenance plan based on the analysis of correlations between flaw progression and boiler operation environment, etc.

1. Introduction

Since products of Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI), such as power plants, are operated in harsh environments over long periods of time, there is a concern about facility damage due to aging degradation. A power plant facility is composed of various types of piping systems. A leak due to damage at any point in the piping systems may lead to an unplanned shutdown of the entire facility for several weeks, resulting in serious consequences for electric power operators and society.

There are two approaches to maintenance: time-based maintenance (hereinafter referred to as TBM) and condition-based maintenance (hereinafter referred to as CBM). The former is to prevent unplanned shutdowns by replacing pipes at regular intervals regardless of the status of facility damage. The latter involves scheduling necessary maintenance activities according to the results of inspection/monitoring of facility conditions. TBM can therefore minimize damage inspection costs. However, it is difficult to achieve both safety and containing inspection costs in the long term, because the only solution for pipes that are at risk of damage is to set a shorter replacement interval, which could lead to excess maintenance. In CBM, on the other hand, necessary maintenance activities are carried out when appropriate according to the facility remaining life inspection results, enabling practical maintenance from both viewpoints of safety and economy[(1)~(3)].

In recent years, thermal power plants have also been responsible for balancing the fluctuations in the renewable energy output, and variable load operation is conducted as needed[(4)]. As society moves toward decarbonization, the transition to new fuels such as biomass, hydrogen

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and ammonia is accelerating[(4),(5)]. Associated risks are therefore expected to emerge, including the occurrence of new damage and the change in the damage progression rate, so demand for CBM-based maintenance is increasing.

Of the various forms of damage seen at facilities, especially worthy of note are flaws on the surface or inside of pipes. These flaws, some examples of which are given in **Figure 1**(a), can exhibit wide-ranging properties depending on the environment in which the product is in use. In assessing the strength and remaining life of a structure, it is critical to have the capability of quantifying the "height (depth) of a flaw" defined in Figure 1(b)[(6)]. However, on-site flaw height measurement in a non-destructive manner demands high levels of skill, causing difficulty in ensuring accuracy. This was a bottleneck in planning CBM-based maintenance. Therefore, MHI developed the TOFD-TFM, a flaw height quantification system based on ultrasonic flaw evaluation technology, which has been made available on the maintenance/after-sales service menu. This report presents our TOFD-TFM system in terms of the flaw height quantification logic, advantages and practical applications, in addition to the background information on the characteristics and issues of conventional inspection methods.

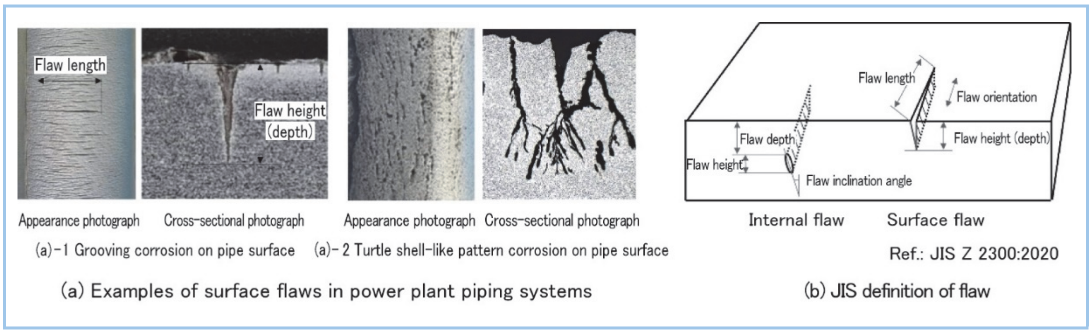

Figure 1 Examples of flaws found in power plants and definition of flaws

2. Widely used methods for flaw height measurement

Generally speaking, the widely used methods of non-destructive testing for flaws in pipes and flaw height measurement are potentiometric method (electrical resistance method), radiographic testing (hereinafter referred to as RT) and ultrasonic testing (hereinafter referred to as UT).

The potentiometric method is applicable only to open surface flaws. In this method, the terminals are placed in contact with the pipe surface to let alternating current flow. When there is a flaw, the current is forced to detour around it. As the distance that the current travels around the wound is related to the amount of voltage drop, the height of a flaw can be estimated based on this correlation. However, the characteristics of electric current means it will take the shortest path regardless of the flaw shape. The measurement values can vary greatly depending on factors such as the positioning of terminals and variable subsurface flaw properties/length. It is therefore difficult to ensure the accuracy of flaw height measurement.

In RT and UT, radiation or ultrasonic waves are sent through the pipe to evaluate the amounts of change, which are correlated with the flaw presence/absence and sizes. The quantification of flaw height is therefore possible in principle. RT necessitates setting up a controlled area during on-site inspection, because radiation is harmful to the human body. In contrast, UT requires no such restriction because of the harmlessness of ultrasound. However, it is technically demanding, as the procedure involves holding the probe by hand to allow ultrasonic waves to directly enter the pipe, and the flaw is examined by observing the change in the waveform.

Figure 2(a) is a conventional UT specified in JIS Z 3060. In UT, the measurement is based on the height information of the reflected echo from a flaw, the positioning of a probe, and the points and range of echo detection. The reliability of measurement results tends to be affected by the inspector's skill level. In recent years, some technologies have provided more objective means to obtain two-dimensional (2D) or three-dimensional (3D) flaw images in real time based on the multi-channel (multi-CH) ultrasonic transmission/reception information. One such widely used technology is the phased array UT, which is shown in Figure 2(b). A multi-CH array probe is made of an array of multiple small oscillator elements, each of which can be excited individually. With appropriately delayed excitation of the individual elements, the focusing points of superposed wavefronts are set in such a way that a 2D or 3D flaw image can be produced by electronically sweeping the angle of propagation. In such UT, an opening in the surface (the root of a flaw) can be detected by corner reflection with high sensitivity. However, the flaw surface or edge (tip of a flaw) cannot be detected/identified by the reflected echo depending on the flaw orientation or inclination angle, causing the actual flaw height to have discrepancies with the positioning of the probe and the points and range of echo detection[7]. Experienced inspectors are therefore pivotal to reliable measurement of flaw height.

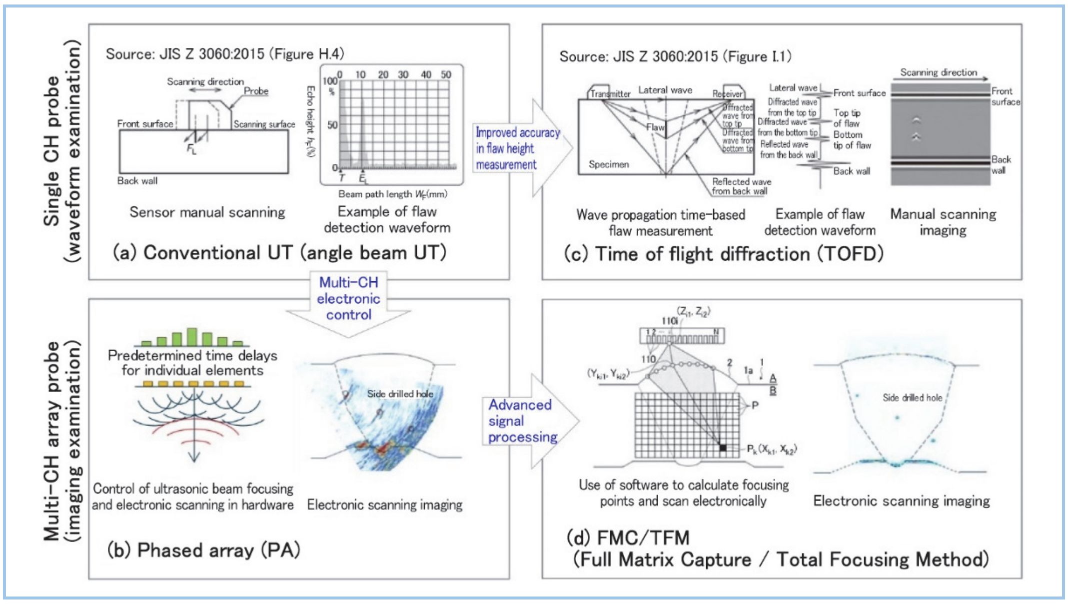

Figure 2 Ultrasonic flaw evaluation technology classification

3. TOFD-TFM ultrasonic imaging system

As a means of quantifying the height of a flaw, TOFD using two probes (transmitter and receiver) was developed as shown in Figure 2(c), and is currently in use. Instead of the reflected echo from a flaw, the diffracted wave from the tip of a flaw is detected. The height of the flaw is measured based on the time of flight of the wave. As diffracted waves are omnidirectional and spherical, the impact of flaw orientation and inclination angle can be relatively small. It is therefore possible to perform robust quantification of flaw height[7]. However, because of the use of single-channel transmission/reception information for measurement, the inability to determine the location of a flaw between the probes is the issue.

In recent years, the development of FMC/TFM (Full Matrix Capture with Total Focusing Method), which is shown in Figure 2(d), has been progressing as one of the methods for accurately determining the location of a flaw, etc., based on the transmission/reception information from multi-CH array probes. In contrast to the aforementioned phased array technology in which the hardware's control of time delays enables an ultrasonic beam to be focused, FMC/TFM is a signal processing technique in which the transmission/reception data are first obtained before being processed using software to calculate the focusing points. It has the advantage that new signal processing logic or ultrasonic beam correction logic is being implemented by improving the programs[8]. Because of the enormous amounts of data handled by such computation, practical application was considered difficult mainly from the viewpoint of processing time. However, the enhanced processing performance of GPGPUs (general-purpose computing on graphics processing units) has now made practical application possible.

Thus, we combined TOFD (for robust assessment of flaw height) with FMC/TFM (which is a multi-CH signal and image processing technology) to develop an ultrasonic imaging flaw evaluation system called TOFD-TFM. The technological development focused on the improvement of reliability, objectivity and storage of measurement results.

Figure 3(a) is a flow chart for our TOFD-TFM system. At least two array probes are used to detect the diffracted wave from the tip of a flaw. However, in the case of examining the large thickness from the outer surface to the depth as shown in Figure 3(b), a flaw that is located away from the convergence point (where the central axis of a transmission beam intersects with that of a reception beam) may not be detected. It is therefore important to identify the area of examination based on the relative distances between the array probes and their angles, and make sure that the inspection should be carried out in the area of interest. As shown in Figure 3(c), propagation of multiple waves is calculated considering longitudinal/transverse waves and reflection modes, thus comprehensively evaluating flaws of varied forms.

In this system, a minimum of two array probes are first set up for the inspection item to obtain all possible waveform data (FMC). The next step is to estimate the positioning (height and angle) of each array probe and their relative distances based on FMC data, etc., which are used to determine the convergence point and examination area in the product and calculate wave propagation. An image of the inside of the pipe is then obtained by performing TFM. As shown in Figure 3(d), a flaw is comprehensively examined by extracting, based on TOFD's principle of operation, the following from the FMC data containing all possible waveform information: (i) a diffracted wave from the flaw tip, (ii) a wave that propagates inside the wedge, (iii) a front-surface-propagating wave (lateral wave), (iv) a reflected wave from the back wall and (v) a reflected wave from the flaw surface. As our system enables real-time imaging of the inside of the pipe, the tracking capability can be checked by scanning in the direction from one probe to another (i.e., horizontal direction in the image). This can make weak, low signal-to-noise (S/N) ratio indications more distinguishable from noise, thus enhancing the detectability. The indications of flaw tips can be identified to estimate the flaw height based on the obtained image.

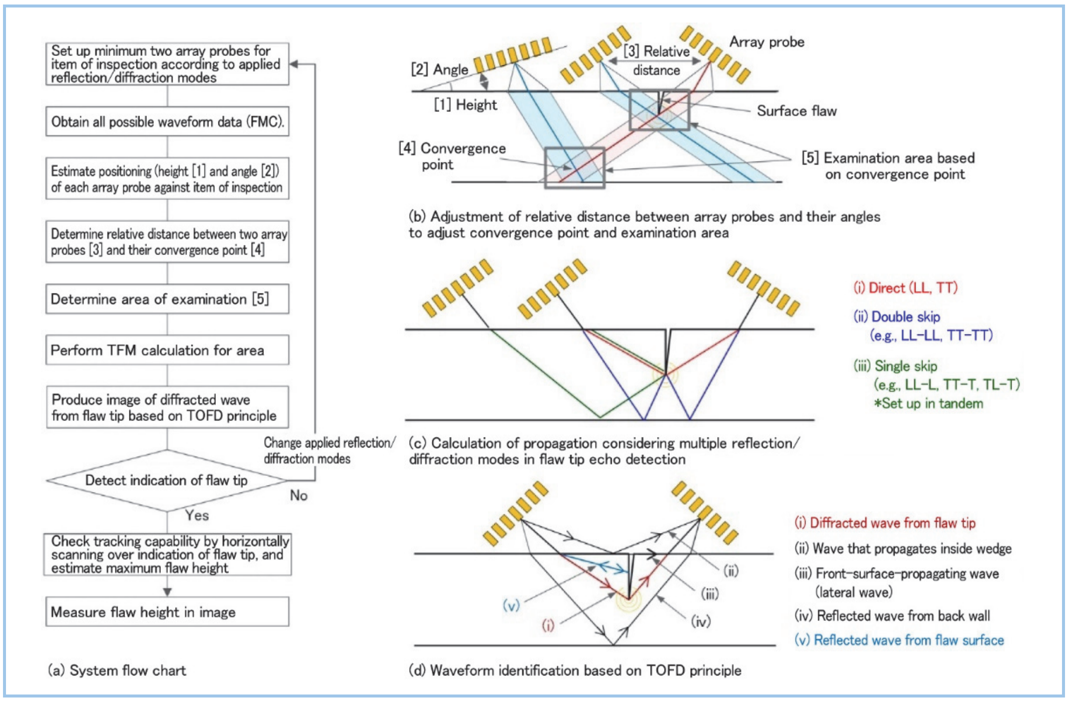

Figure 3 Flaw height measurement method by TOFD-TFM ultrasonic imaging system

4. Technology verification results

4.1 Verification procedure

Targeting the surface flaws with the corroded surface of base material (Figure 1(a)), whose inspection is particularly needed as aging evaluation of thermal power boilers, the validity of flaw height quantification was assessed using both artificial and natural flaws. The artificial flaws are open slits on the surface with the height ranging between 0.5 mm and 2.5 mm. The natural flaws are open flaws on the surface found in actual units. Moreover, with a view to use in weld inspections, we also quantified the height of a flaw artificially made in the weld. This report presents the results of flaw height measurement according to the above-mentioned flow chart of our

TOFD-TFM ultrasonic imaging flaw evaluation system. The measurement results were compared with the actual flaw heights obtained by the following cross-sectional inspection.

4.2 Verification results

Regarding the obtained flaw detection images, some examples of artificial flaws on the surface of the base material are shown in **Figure 4**(a), and those of natural flaws (grooving corrosion and turtle shell-like pattern corrosion) in Figure 4(b). As in Figure 3(c), two array probes were set up opposite each other. With direct scanning or using the double skip technique, the indications of flaw tips were significantly detected, enabling the flaw heights to be measured based on the images. Figure 4(c) compares the actual heights of natural flaws (grooving corrosion) with the measurement results, which indicates the quantification error range of ±0.3 mm. It has also been demonstrated that the flaw tip corresponding to the maximum flaw height can be detected, when the targeted flaws are clustered, connected or branched.

Figure 5(a) gives some of the obtained images of an artificial flaw in the weld. In this testing, two array probes were set up opposite each other, with the weld bead being located in between. The indication of a flaw tip was successfully detected by direct scanning or using a double skip technique. Regarding a surface flaw in the weld toe (Figure 5(b)), the possible positioning of array probes is limited because of the shape of the weld bead. Two array probes were therefore set up in tandem on the same side of the weld line, as in Figure 3(c). This made it possible to detect the reflected/diffracted waves from the flaw surface and tip. For comparison, Figure 5 also shows the flaw detection results of our phased array UT and adaptive UT from above the weld[8],[9]. Although the flaws can be significantly detected by all methods, the TOFD-TFM system provides imaging of the flaw tips, indicating its effectiveness in flaw height quantification.

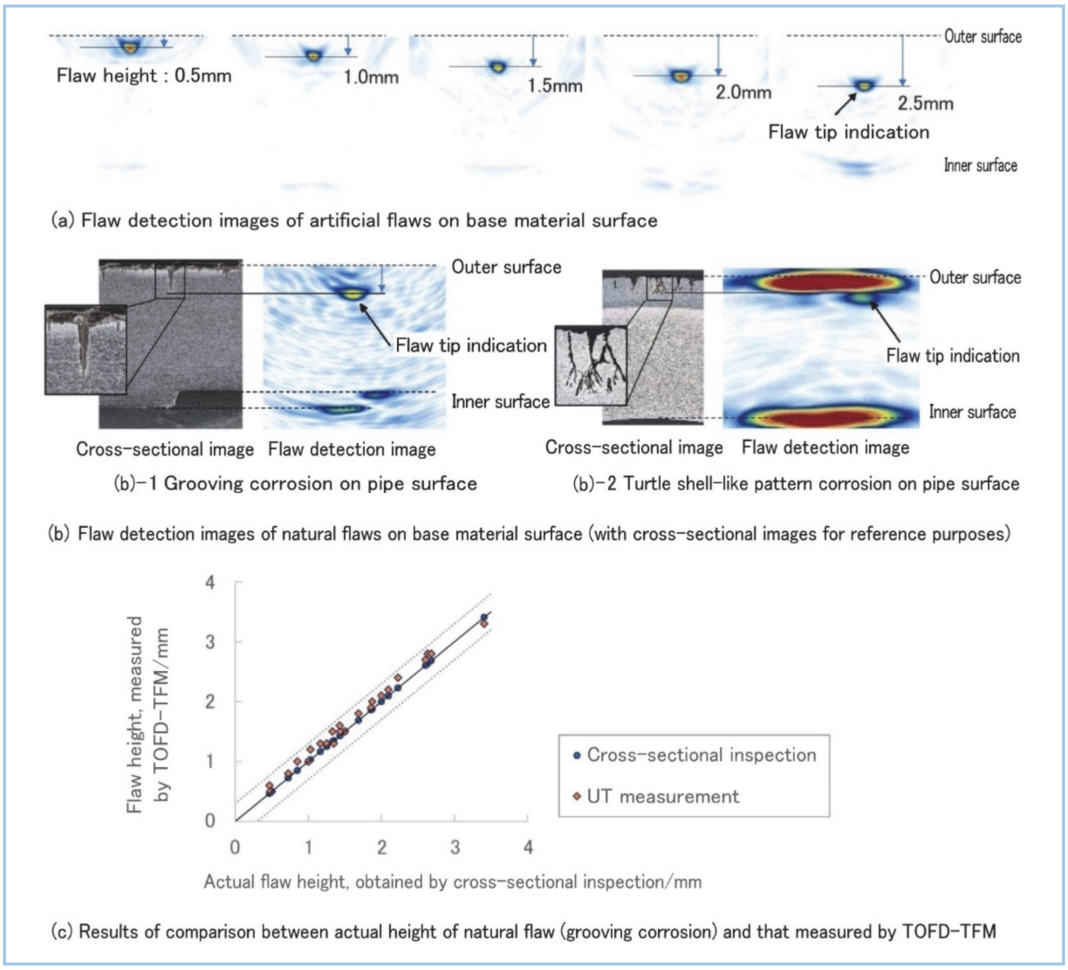

Figure 4 Verification results using surface flaws in base material

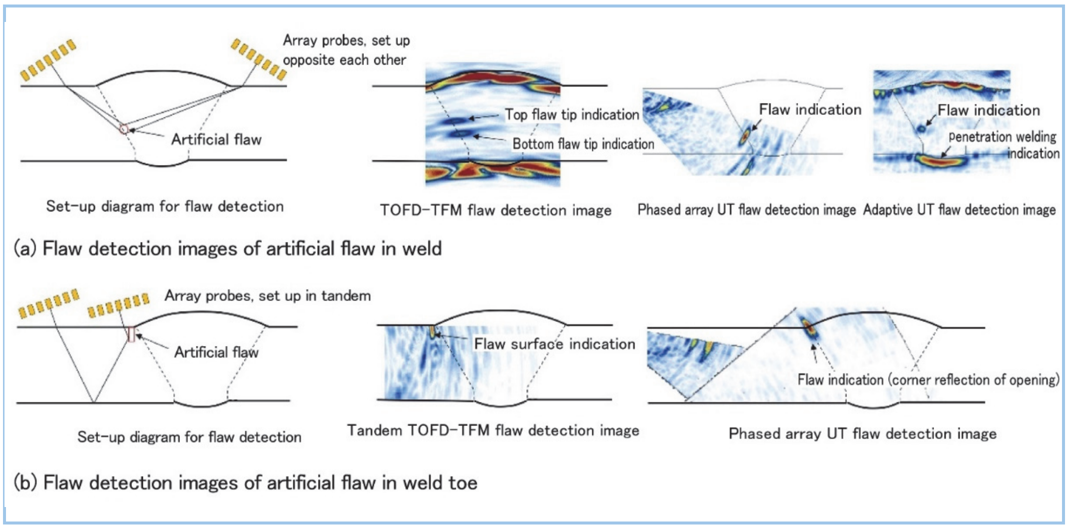

Figure 5 Verification results using flaws in weld

4.3 Discussion and future directions

As described so far, we developed a TOFD-TFM ultrasonic imaging system and demonstrated its ability to perform imaging of the diffracted wave from the flaw tip. Using multiple flaws (those clustered, connected or branched), the flaw heights quantified by TOFD-TFM were compared with the actual flaw heights. The results indicate robust quantification with an accuracy range of ±0.3 mm. Our TOFD-TFM system could be used to quantify flaws in welds, in addition to surface flaws of base material. However, in the case of examining a very small flaw such as a crack with an almost closed opening, further technological improvement and verification are necessary. We are currently evaluating the applicability of the system for various flaw properties and inspection items with varied shapes, materials and thicknesses, with the aim of meeting the flaw height quantification need for multiple products.

5. Practical application

The TOFD-TFM system has been applied to thermal power plants provided by MHI, after confirming in advance the possibility of quantifying the defect height using on-site extubation samples. During on-site inspection, continuous data are collected/stored by scanning piping with array probes, thus completing extensive screening and detection of maximum flaw height simultaneously. The inspection efficiency and the reliability, objectivity and storage of inspection results have been ensured. Developing and introducing a support jig for pipe scanning with array probes should shorten the time required for a series of inspection processes and make the procedure less technically demanding. The maximum flaw height and the remaining pipe wall thickness can be objectively checked by real-time imaging, which enabled us to share the inspection results on the spot with the customer and discuss what to do next.

Regarding some selected flaws that were found in actual units, the temporal study of their heights is currently under way. The obtained results enable us to estimate the rate of flaw progression and analyze the correlation with the boiler operation environment. This helps to make a practical maintenance plan based on the concept of CBM, for example, taking appropriate measures where necessary and evaluating their effects.

6. Conclusion

This report presented our TOFD-TFM ultrasonic imaging system, which is a hybrid of TOFD (for robust assessment of flaw height) and TFM (which is a multi-CH signal and image processing technology). The logic has been constructed in such a way that proper inspection can be conducted despite varied flaw properties, specimen shapes and thicknesses. It has been demonstrated that the optimized positioning of array probes and flaw detection mode can significantly detect the diffracted waves from flaw tips and produce images. A cross-sectional examination was conducted to compare the actual flaw heights with those quantified by TOFD-TFM. The results indicate the robust quantification with an accuracy range of ±0.3 mm. Regarding the flaws that were found in actual thermal power plant units, their height quantification and temporal study are currently under way. The obtained results are used to make a maintenance plan, thereby helping to achieve practical operation from both viewpoints of safety and economy. This technology is versatile and can be applied to quantify damage in various products. It is therefore expected to be used for advanced non-destructive testing on structures in general, including welds as well as thermal/nuclear power plants. While increasing the number of application cases, we will further improve the technology and expand its applicability.

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