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The body can be viewed from the next page.

Automation of Ultrasonic Plate Inspection*


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1 Introduction

Demand for better internal quality of steel plates, including ultra-thick plates, has become increasingly rigorous in line with a growing diversity of use and upgrading of application requirements. Accordingly, ultrasonic inspection, a means of internal quality evaluation, has become more important. With progess in evaluation techniques based on structural fracture mechanics, tolerance limits for internal defects such as lamination which constitute causes of fracturing have been quantified, giving greater importance to the accuracy of ultrasonic inspection.

Ultrasonic inspection of plates includes manual inspection and automatic inspection methods. Manual inspection is frequently used when the fixed location of the automatic ultrasonic test (AUT) system makes its use impossible, especially in consideration of material flow in the manufacturing process and the dimensions and weight of pieces requiring inspection. For manual inspection, each inspector is assigned a qualification in accordance with his knowledge, performance, and experience to ensure ultrasonic inspection accuracy and to guarantee reliability to third parties. Results, however, still vary with the skill of individual inspection personnel. The utmost effort is required to maintain the inspection level, and owing to the poor efficiency of the probing operation itself, an increase in inspection costs is unavoidable.

Automation of ultrasonic plate inspection is comparatively easy to implement, in spite of the highly advanced techniques required, because the shape of plate is simple in comparison with that of other steel products, and the inspection process itself is a repetitive task. Thus AUT systems have long been incorporated in steel mill operation. However, in the field of pressure vessel plates, the applications of which include nuclear power technology, a guarantee of absolute reliability is demanded. To ensure such reliability, automation of ultrasonic inspection of plates, including ultra-thick plates, has become necessary. Furthermore, from the

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viewpoint of quality control, more ultrasonic inspection information has become necessary in order to elucidate the causes of defects and determine measures to prevent their recurrence.

The function and performance of the analog type AUT system,[1] which was introduced in the latter 1970's, has become inadequate for the overall automation of ultrasonic inspection work in terms of computer capacity and the content and speed of information processing. It has also become necessary to reduce the scanning pitch and expand the applicable plate thickness range and to enhance the reliability and economy of ultrasonic inspection. In recent years, improvement in hardware has permitted the development of a digitally-controlled, microcomputer-equipped ultrasonic inspection system,[2] making possible the transfer of high speed signals and advanced automatic control. Software has also improved, allowing reduction of external noise and maintenance of equipment performance, as well as incorporation of the evaluation and judgment functions of ultrasonic inspection results in near perfect accordance with ultrasonic inspection standards for plates. However, the plate thickness range to which the plate AUT system can be applied has limits in terms of ultrasonic inspection performance, because the system uses a double crystal probe, and processing of ultra-thick plates is impossible. As a result, it has become necessary to develop a new AUT system able to cope with a plate thickness range beyond that with which conventional plate ultrasonic test systems are applicable.

This paper discusses the philosophy of automation of the ultrasonic inspection of plates, including ultra-thick plates, and describes the plate AUT system, which was put into service in June 1985 at Mizushima Works, and a portable-type semi-automatic ultrasonic inspection system developed for ultra-thick plates also adopted at Mizushima.

2 Concept of Automation at Mizushima Works

Although plate is simple in shape, the range of thicknesses is wide, from 4.5 mm to 250 mm, and is as great as 300 mm with ultra-thick plate. Automation of ultrasonic inspection to cover the full range of plate thicknesses is difficult in view of the applicable ultrasonic technologies such as optimum frequency and probe type inspection. Further, from the standpoint of production processes the material flow is different for ordinary plate and ultra-thick plate. Thus an effort was made to find optimal solutions to the following problems at the time of automation.

2.1 Division of Functions between AUT and Semi-AUT

The functions of ultrasonic inspection are classified by working element into: (1) calibration and checking of the system, (2) setting-up of test conditions, (3) scanning, (4) recording, and (5) evaluation and judgment. The decision on whether all or a some of these working elements are to be automated is determined by required productivity, economical considerations, including initial investment, and the current state of development of ultrasonic technology.

2.3 System Specification

2.3.1 Plate AUT system

A plate AUT system requires multi-channel techniques because it must have the processing capability to virtually synchronize inspection with the material flow of the production line. However, the cost of an ultrasonic test system is nearly proportionate to the number of channels. Therefore, the following points were taken into consideration in the system specification:

(1) Minimum Construction and Maintenance Cost
Decrease of the number of channels through pitch scanning, and a full-coverage scanning by a repeated scanning operation, as necessary.

(2) Improvement in Ultrasonic Inspection Performance
Increase in inspection accuracy in the periphery area of the plate, considering that the area is subject to secondary processes such as welding and machining. Further, external noise must be minimized.

(3) Enhancement of Automated Function
Full automation of operational elements of the ultrasonic inspection system, and a monitoring capability of the AUT system.

(4) Simplification of Maintenance
Mechanism for easy adjustment of necessary water gap between probe and inspection surface and easy probe replacement to ensure satisfactory inspection conditions at all times. Addition of an anomaly diagnosis function was to inform the operator when system performance deteriorates beyond the control level.

2.3.2 Ultra-thick plate AUT system

The ultra-thick plate AUT system is of a portable, disassembable, semi-automatic type; the design was based on the following considerations:

(1) Decreased Component Weight
Since assembly and disassembly of the system are carried out manually, the assembly is to be modular, with the weight of sub-units made light enough to permit manual handling. The optimum number of channels should be decided with on this basis.

(2) Simplification of Scanning
Full-surface scanning is to be used generally, but pitch scanning should also be used as required.

(3) Recording of Inspection Results
Accurate defect positions will be indicated by the numerical display, and defect positions and their distributions will be visualized by a graphic display in the plane and cross-section directions. Inspection conditions are recorded.

2.4 Inspection Capabilities

(1) Plate AUT System
To cope with high volume production, the overall cycle time required shortening. An AUT capacity of 10 000 pieces per month was provided.

(2) Ultra-Thick Plate Semi-AUT System
Since the number of ultra-thick plates requiring ultrasonic inspection is few, there is no need to synchronize inspection with the line production rate. Therefore, no increase of processing capability over the current manual ultrasonic inspection capacity was required.

3 Functions and Features of Plate AUT System

The functions and features of the AUT system for plates having a plate thickness of up to 60 mm are shown below.

3.1 Layout

The layout of the AUT line is shown in **Fig. 1**. Plates requiring ultrasonic inspeciton are automatically stopped on the on-line table at the crane take-up position and transported to the scanning table by a crane operated from the ultrasonic operation room. The plate, after completion of ultrasonic inspection, is returned to the on-line table by a semi-automatic crane.

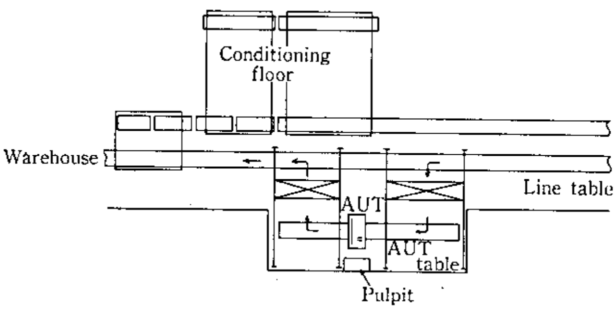


Fig. 1 Layout of plate-AUT

3.2 Outline of System

The alignment of mechanical components in the plate AUT system is shown in **Fig. 2**; the basic specification

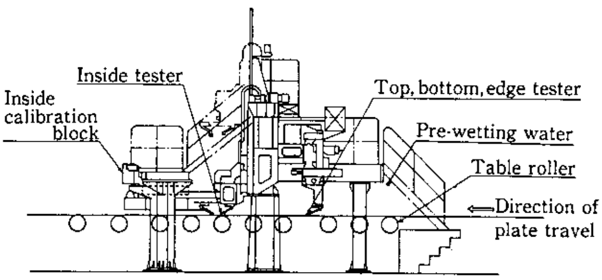


Fig. 2 AUT alignment of mechanical components

Table 1 General specification of automatic ultrasonic tester (AUT) for steel plates

Item	Specification
Material	
Thickness	6.0～60.0 mm
Width	900～5 400 mm
Length	2 900～25 000 mm
Method	Water gap type double crystal probe pulse echo technique
Scanning pattern	
Pattern I	Periphery + horizontal line of 75 mm pitch
Pattern II	Periphery + 100% coverage
Scanning speed	
Inside, side edge	60 m/min
Top/Bottom	40 m/min
Probe	
Inside	5Z6 × 25ND
Periphery	5Z6 × 25ND + 5Z6 × 10ND
Number of channel	
Inside	70 ch
Top/Bottom	10 ch
Edge	8 ch × 2
Calibration	Fully automatic control for gain, flow gate, DAC, self-check
Record	· Line printer · C-scope display on CRT · C-scope color hard copy
Others	· Gate monitoring on bottom echo · Automatic gain control

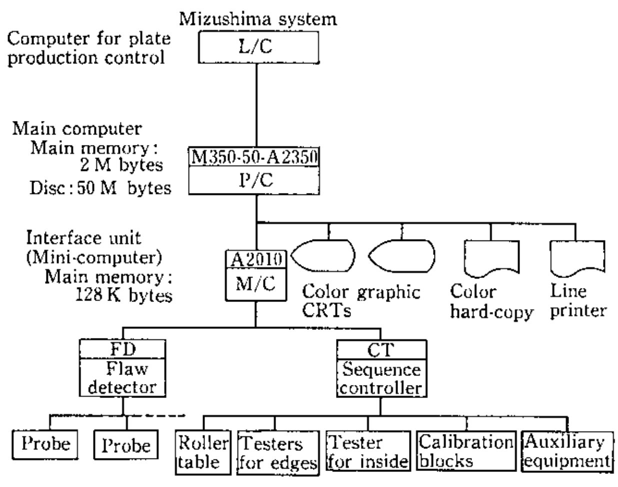


Fig. 3 Computer system

of the system is shown in **Table 1**. The configuration of the computer system is shown in **Fig. 3**. The process computer for the system is connected to the line computer. Information regarding the plate to be inspected and the ultrasonic inspection conditions are supplied by computer, and automatic ultrasonic inspection is performed. The results of the ultrasonic inspection are then fed into the line computer. This system inspects a plate in about 120 s; its monthly inspection capacity is about 14 000 pieces.

3.3 Features of System

3.3.1 Characteristics of system design

Scanning is divided into three modes. Pitch scanning in the rolling direction is used as a basis. Full-coverage scanning is also possible by adopting the repeat mode as required. The three modes are:

Model 1: Internal longitudinal direction 75-mm pitch and periphery 100-mm width full coverage scanning

Model 2: Internal, repeated 3-times and periphery 100-mm width full coverage scanning

Model 3: Internal, repeated 4-times overlap full coverage and periphery 100-mm width full coverage scanning

Here the term "periphery 100 mm" means that the four edges, the top, bottom, and two sides, of the plate are given 100-mm width full coverage scanning.

The reasons for adopting pitch scanning were: (1) Pitch scanning is mainly adopted in the ultrasonic standard, (2) full coverage equipment at one scanning is high in construction cost, and (3) a smaller the number of probes makes maintenance easier.

Rolling direction scanning was adopted because improvement in the S/N ratio made it possible to increase sensitivity of rolling direction scanning to the small level of vertical-direction scanning, and also because of the reduction of scanning cycle time attributable to the change of scanning direction. The scanning pattern in the basic scanning mode is shown in **Fig. 4**.

3.3.2 Automatic calibration and checking

An outline of the automatic calibration function is shown in **Table 2**. Movements of the probe on the calibration block are shown in **Fig. 5**.

It is a characteristic feature of this calibration and checking function that effective beam-width measurements of all probes can be made simultaneously.[3] A 10-mm thick calibration block having an artificial defect 7 mm in depth and 5 mm in width is scanned, as shown in **Fig. 6**, in the width direction of a calibration block by a probe, and scanned image is produced as shown in **Fig. 7**. An effective beam width of −3 dB or −6 dB in the probe width direction can be automatically measured. In the checking function, the flaw echo level (F_1) from the slit defect and the sound echo (B_1) are measured, and from the ratio between F_1 and B_1, the setting condition (tilting) of the probe is judged.

Checking is periodically performed in this manner, ensuring proper functioning of the probe, and plays an important role in securing the accuracy of the ultrasonic inspection system.

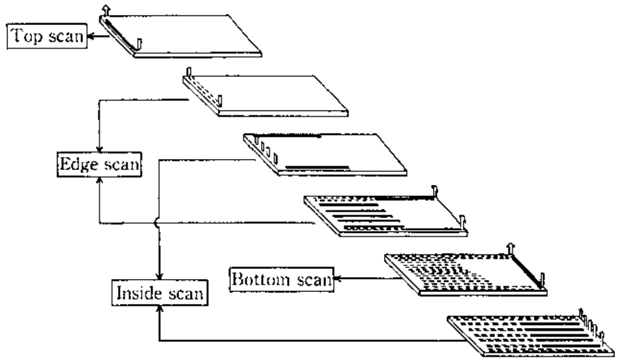


Fig. 4 AUT scanning mode

Table 2 Function of calibration check and self-control

Calibration	Check	Self-control
1. Gain 2. DAC 3. Gate	1. DAC 2. F/B 3. Amplitude linearity 4. Time base linearity 5. Mock UT	1. Self-check 2. UST I/F check of signal

DAC: Distance Amplitude Compensation
F/B: Flaw echo/Bottom echo
I/F: Interface

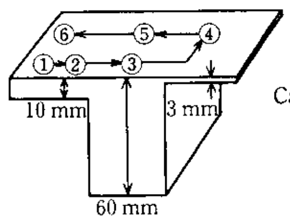


Fig. 5 Calibration method and calibration block

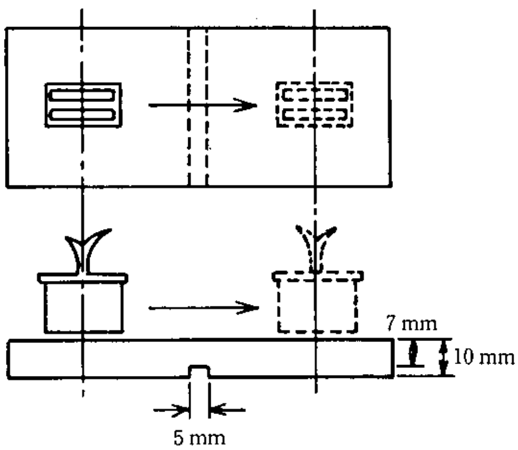


Fig. 6 Measurement of the effective beam width of the probe

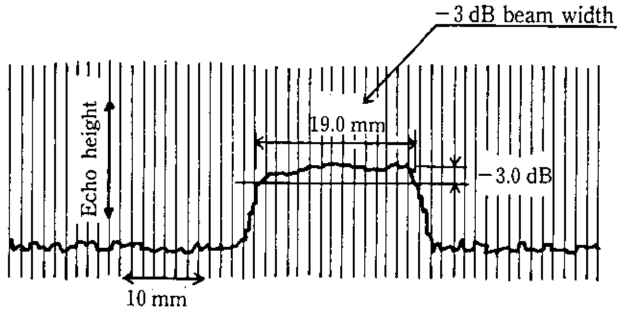


Fig. 7 Analogue chart of effective beam

3.3.3 Countermeasures against quasi-defects[4)]

One problem affecting the accuracy of AUT is quasi-defects due to noise. Conceivable causes of noise are noise generated by probe malfunction and surface irregularities of the plate such as shearing fins, grinder traces, and dirt. Quasi-defects are generally caused by problems with the plate surface. The present system is provided with the following measures against such plate-surface quasi-defects:

(1) Removal of Protrusions on Plate Surface
An example of a quasi-defect caused by irregularities of the plate surface is shown in **Fig. 8**. When the surface is normal, the distance between the probe and plate surface is about 0.3 to 0.5 mm and the surface echo (S_1) reflected from the plate surface is several percent, which is below the threshold level. However, when protrusions such as surface defects and shearing fins exist, the water gap distance increases, causing an increase in the surface echo level; this is registered as a defect though in fact it is a quasi-defect. As a countermeasure, the present system is provided with a dummy probe head on both sides of the plate as shown in **Fig. 9**.

(2) Changed Ground Trace Direction
When the ground trace direction on the plate surface is in parallel with the probe-width direction, reflections from the ditch of the ground traces are of a high level, and quasi-defects are likely to occur. To cope with this, the direction of the ground traces is changed to lie transverse to the probe width direction.

(3) Cleaning of Plate Surface
When dust or some other foreign substance is present on the plate surface, quasi-defects are likely to occur for the same reason as that mentioned in Item (1). For this reason, the plate surface is cleaned by twice-repeated pre-wetting and wiping before the plate is inspected by the system.

The measures in Items (1) ~ (3) above, quasi-defects have been reduced by half; however, more accurate AUT will require an even more sophisticated level of inspection accuracy involving improved discrimination between defect signals and noise signals, from both the hard and software aspects.

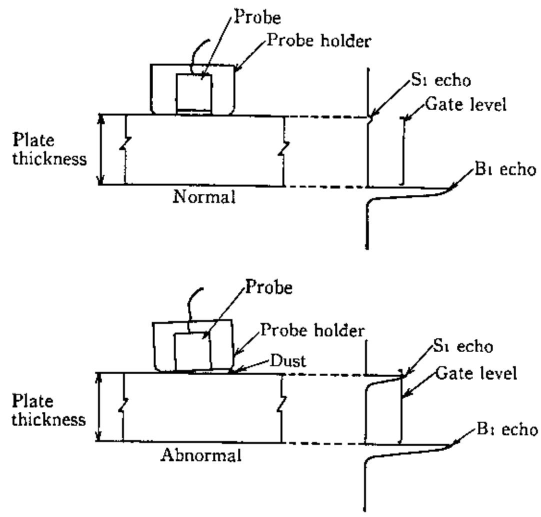


Fig. 8 Schematic figure of surface echo increasing mechanism

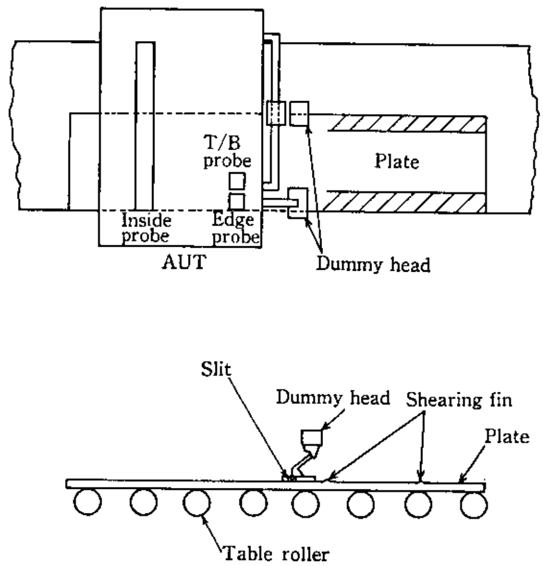


Fig. 9 Dummy head positions on the plate

3.4 Ultrasonic Inspection Records

An example of detectability verification with the present system is shown in **Fig. 10**. This is an analogue chart of the ultrasonic inspection of flat-bottom drilled holes (artificial defects) measuring 5.6 mm, 4.0 mm, 2.8 mm, and 2.0 mm in diameter, made on a 40-mm thick plate. In the test, artificial defects of even the minimum 2-mm diameter were detected. With natural defects, the reflection echo level drops with certain flaw shapes. Assuming that a defect size twice as large as the area of the artificial defect is taken as the detection limit for

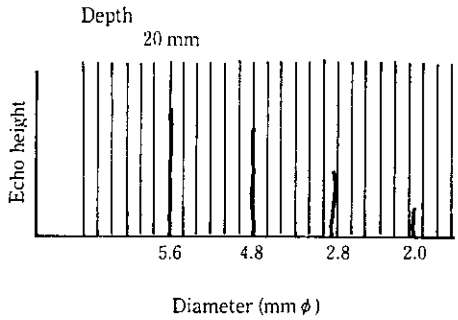
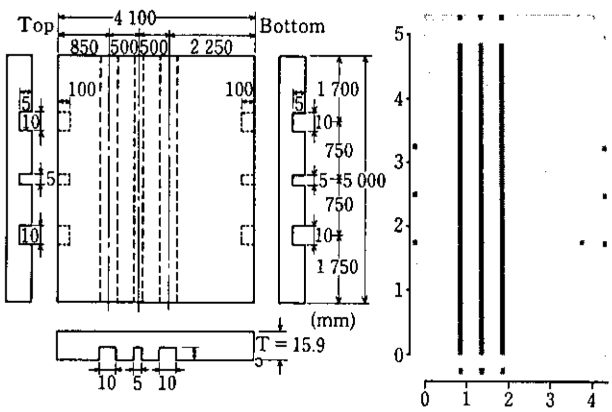


Fig. 10 Analogue chart of artificial defect (flat bottom drill hole)



(a) Artificial defect (b) C-scope map

Fig. 11 Schematic figure of artificial defect and C-scope map

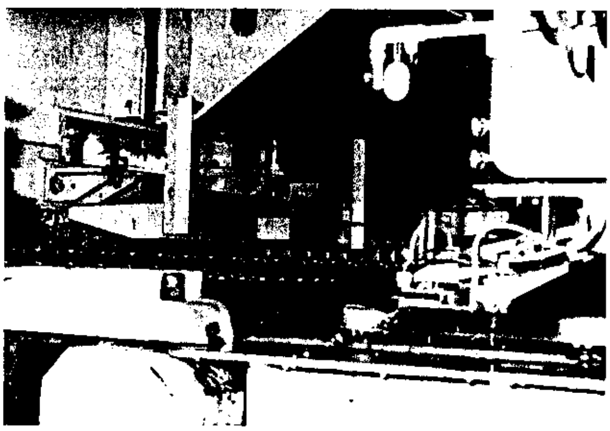


Photo 1 Side view of probe alignment

natural defects, it is considered that a defect 2.8 mm in diameter can be adequately detected. Further, **Fig. 11** shows C-scope results when a slit defect prepared on a UOE-pipe-quality plate for use in dynamic calibration was inspected using scanning mode 1. These results indicate that all probes have detected artificial defects at the threshold level as the M-level, proving the soundness of the system. Side and inside views of the probe alignment are shown in **Photo 1**.

4 Functions and Features of Semi-AUT System for Ultra-Thick Plate

Functions and features of the automatic ultrasonic test system[5] for ultra-thick plates of thicknesses exceeding 60 mm are discussed below.

4.1 Outline of System

An outline of the system is shown in **Fig. 12**; a general view of the inspection device is shown in **Photo 2**. The system consists of the following three components:

(1) The scanning unit, which performs automatic scanning using 4-channel probes.

(2) A control device, equipped with a detector, CPU, and printer, which performs inspection control, processing of inspection data, and data printout.

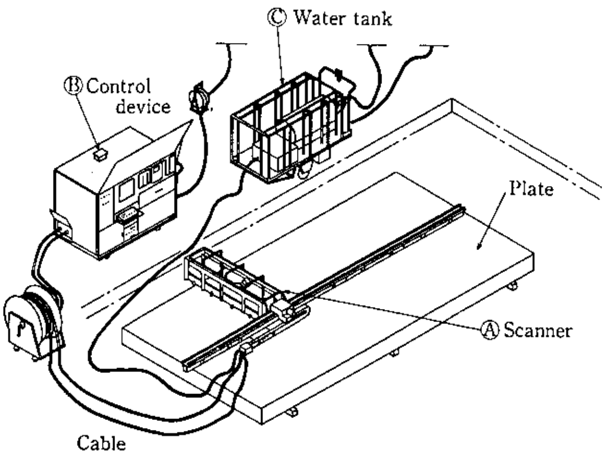


Fig. 12 Scope of the heavy thickness plate testing component

Photo 2 View of ultra-thick plate-AUT scanner device

Table 3 General specification of ultra-thick plate AUT

Item	Specification
Material	
Thickness	160～300 mm
Width	1 000～5 000 mm
Length	1 000～15 000 mm
Method	Immersion type normal probe pulse echo technique
Scanning pattern	Periphery inside, 100% coverage (25 mm pitch scanning)
Scanning speed	30 mm/s～300 mm/s
Probe	2.25Z28～30I×4 ch
Recording	· Line-printer
	· C-scope record on CRT
Others	· Gate monitoring on B echo
	· Automatic gain control
	· Portable scanner

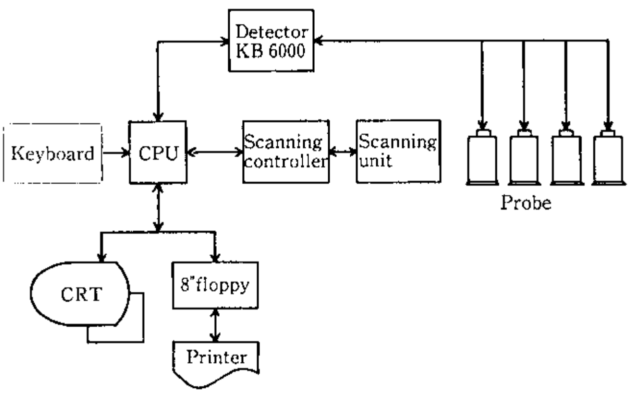


Fig. 13 Block diagram of AUT system

(3) A water supply unit, which provides water for coupling in the actual inspection process and for the rails on which the scanning unit runs.

The general specification of the system and the system configuration are shown in **Table 3** and **Fig. 13** respectively. When performing an inspection, these three modules are moved to the vicinity of the ultra-thick plate to be inspected. Next, the scanning rail is laid on the piece and the scanning unit is installed. After setting up of the components, inspection conditions are supplied to the scanner and the operation is controlled by personal computer.

4.2 Features of System Design

4.2.1 Portability

The following measures were adopted to allow easy movement of the unit to the inspection location:

(1) The entire system consists of three modules: the scanning unit, controller, and water supply unit.

(2) The scanning unit can be disassembled into the scanning rail, probe, and scanner, which are then reassembled on the inspection piece at the operation site.

(3) Each bolck of the inspection unit is mainly of aluminum alloy; the weight of each block is under 25 kg.

(4) The water supply unit is motor driven and serves as a conveyance for the respective blocks of the scanning unit, which are designed to fit in it.

4.2.2 Scanning mode

The main scanning mode is 25-mm pitch full-coverage scanning (full coverage by an overlap of 10% of the ultrasonic probe diameter on each scanning pass). The unit also permits pitch scanning. When scanning is performed, the one-pass range is limited by its characteristics as a portable scanning unit, so a plate is scanned in several passes. The one-pass scanning range is 1.7 m max. $W \times 4$ m max. L.

4.2.3 Processing and recording of inspection results

Inspection data is stored sequentially for each pass on a floppy disk. The detection signal from the detector and the position signal from the scanner are used to judge the defect level at 2-mm pitches, then defect levels are integrated into a 100-mm pitch, and finally inspection data for all passes is synthesized. The final result is output as the inspection result for the entire piece in the form of a C-scope map. The recording method consists of real-time color display, a C-scope map of the synthesized inspection result, and lists of echo levels and positions of flaw indications.

An example of detectability verification with the system is given in **Fig. 14**, which shows a C-scope map of inspection results of a 150-mm thick plate with flat-bottom drilled holes 30 mm in depth and 2.0, 4.0, and 10.0 mm in diameter. The results indicate that artificial defects down to 2.0 mm in diameter can be detected. **Figure 15** shows the synthesized inspection results for a

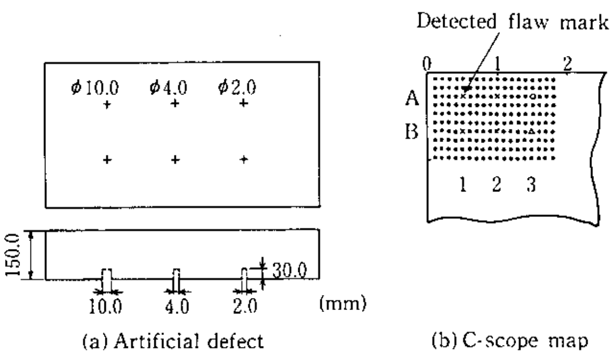


Fig. 14 Schematic figure of artificial defect and C-scope map

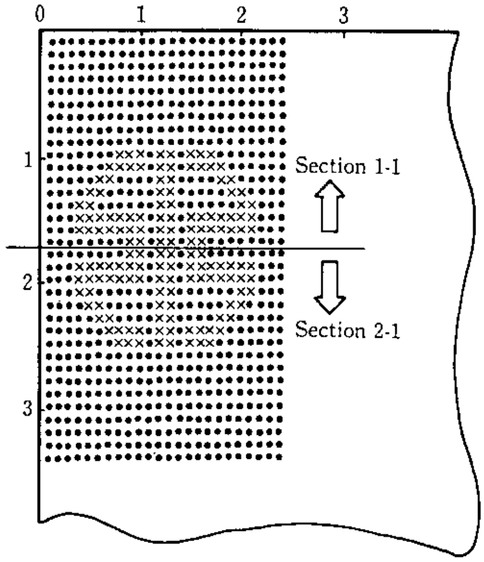


Fig. 15 Synthetic C-scope map

series of inspection passes.

The above mentioned results demonstrate that both the detectability and recording accuracy targetted in the initial plan have been achieved.

5 Conclusions

The philosophy and current state of development of automation of the ultrasonic inspection system for steel plates at Mizushima Works have been discussed. Ultrasonic inspection of plates, including ultra-thick plates has demonstrated the reliability of the inspection system to objective observers, including some customers. Furthermore, economic benefits have been realized by automation. Main characteristics of the system design are as follows:

(1) Plate AUT System

(a) The system is basically designed for pitch scanning, but through repetition of scanning, it is also available to perform full coverage inspection.

(b) Detectability capable of detecting flat-bottom artificial defects as small as 2 mm in diameter has been proven.

(c) Full automation has been achieved in the calibration and checking of functions, including the probe, and the overall performance of the system.

(d) Ultrasonic inspection results can be automatically evaluated and judged according to given standards.

(e) Through use of measures such as the dummy probe head and others, quasi-defects have been reduced.

Following the improvements described above, the system has demonstrated its high reliability and economy in operation.

(2) Ultra-thick Plate Semi-AUT System

(a) Automation of scanning, data processing, and recording has been achieved.

(b) Manual disassembly/reassembly makes the unit portable.

(c) Detectability down to 2 mm in diameter has been verified.

Thanks to these features, the system has won high acclaim in the field of ultrasonic inspection of ultra-thick plate for nuclear power use and other critical applications.

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