Application of Phased Array Ultrasonic Transducer to Pipe and Tube Inspection*

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Synopsis:

Specific flaws or defects on the inside surface of pipe cannot easily be detected by existing non-destructive methods. The authors have developed a new non-destructive tester, using ultrasonic phased array elements, which can inspect on-line the inside surface flaws and other defects. The linear array probe consists of ultrasonic vibration elements sliced into 128 bits, and its sensitivity characteristics are kept constant to within 0.4 dB. The linear array probe is mounted in a water bath at the site, and the pipe to be inspected is arranged in a spiral in the bath for scanning electrically by the linear array probe. Ultrasonic echo signals are processed by computer and displayed on a B + C scope. This advanced inspection method is applied to seamless pipe, including that in stainless steel, and is inspecting inside surface flaws at a high S/N ratio.

1 Introduction

Steel pipe is one of the final products of steel, and is frequently used by customers in the condition delivered from the factory. Consequently, meticulous care is taken with product inspection. In particular, non-destructive inspection techniques have assumed the greatest importance for steel pipe inspection and quality assurance, and there is a history of active introduction of up-to-date techniques. The recent trend of small-lot, multi-kind production has made the demands for the quality of steel pipe increasingly more rigorous.

A steel-pipe product inspection system and enhanced productivity in product inspection to satisfy such quality demands by customers have become important requirements.

Chita Works of Kawasaki Steel Corp. has, as part of the development of an inspection system, paid particular attention to inside surface inspection, which has relied on human visual in the past, and has developed the techniques to carry out this inspection by using a non-destructive tester. The purpose of this non-destructive tester is to enhance the quality assurance level of the inside surface of steel pipe and to automate ultrasonic tester operation. This non-destructive tester uses ultrasonic phased array elements,[1-3] which is one of the most up-to-date techniques. The application of these ultrasonic phased array elements has made it possible to improve flaw detection to a level that is impossible to achieve by conventional non-destructive inspection techniques. Pipe size restriction has been removed by arranging the phased array elements in a water bath in the longitudinal direction of the steel pipe ("size switching free" method).

This paper reports the development of this non-destructive tester using ultrasonic phased array elements, reasons for its adoption, principles of detection by ultrasonic phased array elements, mechanism for realizing highspeed detection of inside surface flaw of entire length of pipe from outside, and results of its on-line operation.

2 Conventional Non-destructive Inspection Techniques

It is well known that on-line non-destructive inspection techniques can be broadly divided into methods utilizing the reflection or permeation of ultrasonic waves, methods for detecting magnetic leakage flux from a defect by using DC or AC magnetization, and methods for detecting impedance fluctuations by using the eddy current. All these methods have, after extensive studies, become established non-destructive tech-

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niques and are being applied to the flaw detection of steel pipe.

However, these flaw-detecting techniques have several inherent problems that make it difficult to automate visual inspection of the inside surface of steel pipe and to apply the non-destructive tester to on-line operation.

Ultrasonic techniques are most widely used for the non-destructive inspection of steel pipe, but suffer from the following drawbacks:

(1) Stainless steel materials have larger grains compared with carbon steel, which results in noticable scattering and resultant attenuation of the ultrasonic beams.

(2) In the case of slowly changing defects on the inside surface of steel pipe, as shown in **Fig. 1**, such defects sometimes do not act as a reflecting source for the ultrasonic beams. Since no reflection echoes can be obtained, flaw detection sometimes becomes impossible.

(3) In the case of a sharp defect that runs nearly parallel to the surface of the steel pipe as shown in Fig. 1, the applied ultrasonic beams create multiple reflections and become attenuated, thereby causing the beams to fail in their function as a reflecting source.

The magnetic leakage flux techniques are comparatively new for non-destructive inspection, but since the following drawbacks have been pointed out, these techniques cannot be used for rigorous flaw detection:

(1) In the case of a material having a permeability of "1" as for austenite material, the magnetic leakage flux is non-existent, and flaw detection is impossible.

(2) Chromium molybdenum steel material shows, under the influence of its fine ferrite texture, behavior like that of a magnetic material, and the background noise increases, thereby sometimes making it impossible to obtain a satisfactory *S/N* ratio.

(3) In the same way as for ultrasonic beams, when a defect on the outside surface of steel pipe slowly changes (shown in **Fig. 2**), there is no sudden change in the potential; hence the magnetic flux flows away along the outside surface of the pipe. Thus, the magnetic leakage flux is lost, preventing the execution of flaw detection.

(4) From a defect which is pressure-welded hard to the outside surface of steel pipe, no magnetic leakage flux is generated and flaw detection is impossible.

(5) Even if AC or DC magnetization is used, the magnetic leakage flux from a defect on the inside surface of steel pipe is easily attenuated, making rigorous flaw detection difficult.

Eddy current techniques have been applied to practical use for longer than ultrasonic techniques, but the following problems exist:

(1) Through the skin effect of AC magnetization, the eddy current, like magnetic leakage flux, is not suitable for detecting small-scale defects on the inside surface of steel pipe.

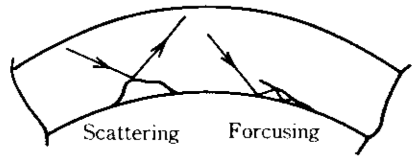

Fig. 1 Propagation of ultrasonic beam

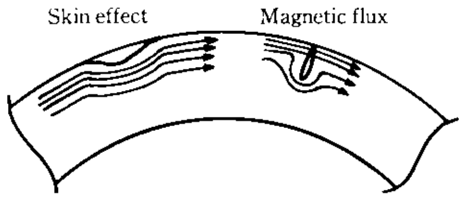

Fig. 2 Magnetic flux flow on magnetic leakage flux test

(2) It is well known that a defect in the longitudinal direction of steel pipe shows a small fluctuation in impedance, and the detection ability of the eddy technique is low.

(3) When the tunnel-type probe coil is used, the "size switching free" method can not be used. Further, when the rotary-type probe coil is applied, detection of a defect on the inside surface of steel pipe becomes impossible due to the skin effect of AC magnetization.

(4) The insertion-type probe coil has also been put into practical use,[4] but it requires a shuttling motion, thereby making automation very difficult.

These problems have made it necessary to develop a new non-destructive inspection technique that would be most suitable for automating the visual inspection of the inside surface of steel pipe.

3 Development of the Detection Principle

3.1 Examination of Detection Methods

To accurately detect a flaw lying on the inside surface of steel pipe, flaw detection methods were examined which satisfy the following development requirements:

(1) Applicable to any type of steel (to facilitate flaw detection of carbon steel and stainless steel)

(2) Able to detect flaws over the entire surface (to make full surface flaw detection possible by a skew-processing line)

(3) Applicable to any pipe sizes (to dispense with setting to meet changes of outside diameter and wall thickness of pipe)

(4) Applicable to flaw detection from the outside of steel pipe (without inserting the flaw detector inside the pipe)

(5) Able to produce the projected profile of a defect.[5]

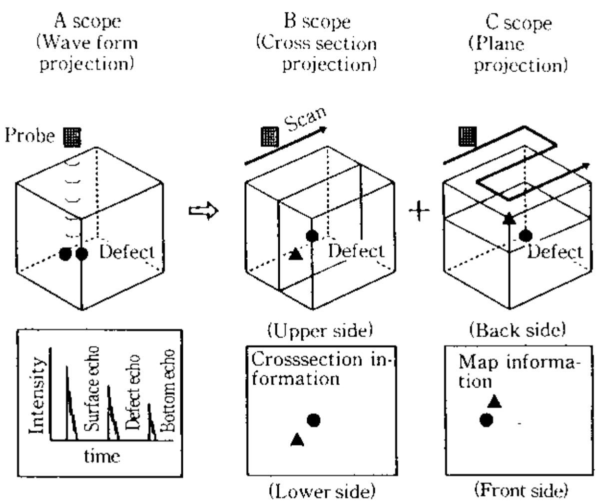

Fig. 3 Presentation of ultrasonic scope

Of the several non-destructive inspection methods applicable to steel pipe as outlined above, study was made on various methods for detecting flaws lying on the inside surface of steel pipe from outside. As a result, the authors reached the conclusion that the ultrasonic flaw detection method would be the most suitable due to its basic principle and ease of signal processing.

To indicate flaw detection waveforms with the ultrasonic flaw detection method, there are the A, B and C scopes illustrated in **Fig. 3**. The A scope is the most basic indication method with ultrasonic flaw detection by which the ordinate of the waveform represents the echo height, and the abscissa represents the time (distance), thereby giving information about echo height and time (distance) up to the reflection source. With B scope, the probe moves parallel to the material being inspected, the scanning distance being represented by the abscissa, and the distance to the reflection source by the ordinate which gives brilliance modulation to the echo height, thereby obtaining a sectional projection of the material to be inspected. The C scope scans the probe in a rectangular motion across the material being inspected and a plan (permeated) projection of the material is given. By combined use of B scope and C scope, it is possible to obtain a 3-dimensional profile of the defect existing in the material being inspected. However, in order to obtain B scope and C scope projections by conventional techniques, it is necessary to mechanically traverse the ultrasonic probe; hence, it has been difficult to use such a method for the high-speed inspection required in a steel pipe manufacturing line.

Recent application in the medical field of a linear array probe has enabled a B scope projection to be produced by electronic scanning of the ultrasonic probe. This linear array probe consists of multiple piezo elements aligned in about 1 to 2 mm slices. Excitation of these multiple piezo elements (i.e., ultrasonic vibration elements) as a group provides ultrasonic beams of a prescribed intensity, and by sequentially switching over electronically the vibrating elements, it is possible to obtain the B scope projection directly under the linear array probe. However, medical equipment inspects the human being and is used on nearly static objects; hence, its signal transmitting power and inspection speed (repeat frequency) are both low, and it cannot be used directly for steel pipe making. Especially in the case of a material having large grains such as stainless steel, a low transmitting power is fatal. Therefore, the linear array elements were modified in order to enhance their transmitting power and to obtain ultrasonic beams in a higher frequency band.

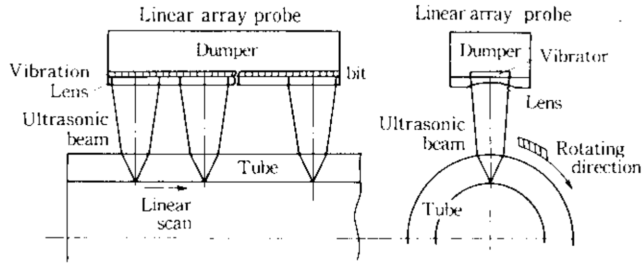

Fig. 4 Testing principle by linear array probe

3.2 Detection Principle

The principle for steel pipe inside surface flaw detection by the linear array probe is shown in **Fig. 4**. The linear array probe is arranged parallel to the steel pipe, and can scan the entire outside surface of the pipe in its longitudinal direction. It is an instantaneous electronical scan within the length of the linear array probe, and the pipe under inspection is rotated by the unit length of the linear array probe.

By vertical propagation of the ultrasonic beams on to the steel pipe surface, it is possible to obtain the top surface echo as well as the defect echo and bottom echo across the wall thickness. Processing the data of these echoes and scanning parameters by a personal computer provides the B scope and C scope projections.

3.3 Trial for Commercial Production

In order to judge whether or not the linear array probe was suitable for detecting the inside surface defects of steel pipe, a linear array probe was constructed with a flaw detection frequency of 5 MHz, vibrating element dimension of 2 mm × 16 mm, and 64 elements in total. Using this trial probe, the authors investigated the B scope projection of various artificial defects created on a steel plate. An example of the results is shown in **Fig. 5**. Electeronic scanning by the linear array probe was carried out by making eight elements into one group and by units of a single element. As a result, a B scope projection similar to the sectional shape of a scab-shaped artificial defect ($\theta = 20°$, depth = 2 mm) was

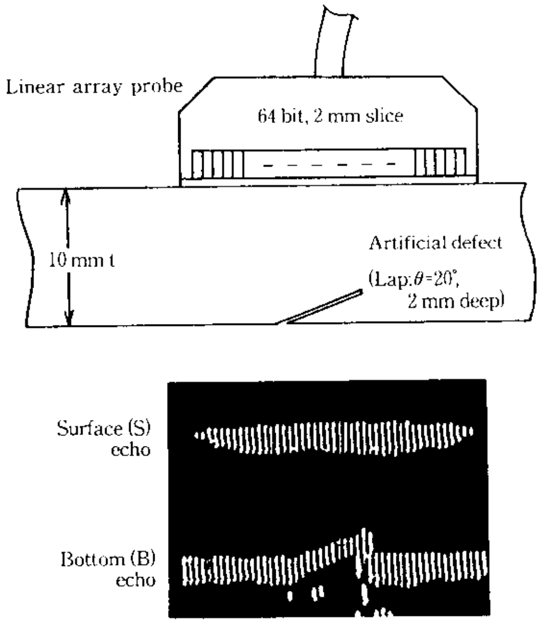

Fig. 5 An example of B scope projection (Scan mode: 8 bit group, 1 bit shift)

obtained. These results suggested that it would be possible to detect the inside surface flaws of steel pipe by using a linear array probe.

When this probe is finally applied to the production line, the layout shown in Fig. 4 will be adopted. By placing the probe into a water bath and arranging it under the steel pipe, it is possible to detect flaws regardless of the outside diameter of the pipe. Thus, an online flaw detector can be provided that will not require its insertion into the steel pipe and that can handle a wide range of pipe sizes.

4 Outline of the On-line Flaw Detector

4.1 Static Characteristics of the Linear Array Probe

Detailed specifications of the linear array probe that has been developed for on-line use are shown in **Table 1**. This is a 5-MHz linear array probe in which 128 vibrating elements measuring 2 mm × 16 mm are aligned. The authors have investigated the sensitivity and phase of each vibrating element in this linear array

Table 1 Specifications of linear array probe

Type	5C2-161 J-128 ch
Sensor material	Lead titanate
Sensor dimensions	256 mm length × 16 mm width
Elements	128 bit
Lens material	Polyether resin
Focal distance	60 mm in water

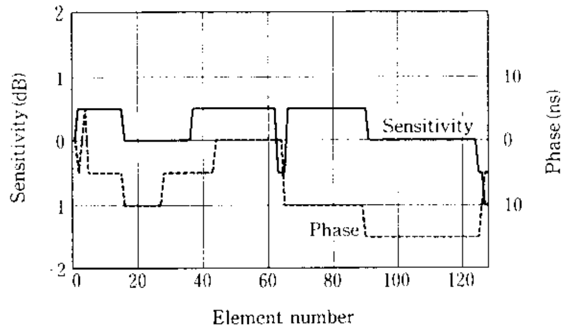

Fig. 6 Distribution of sensitivity and phase between sliced elements

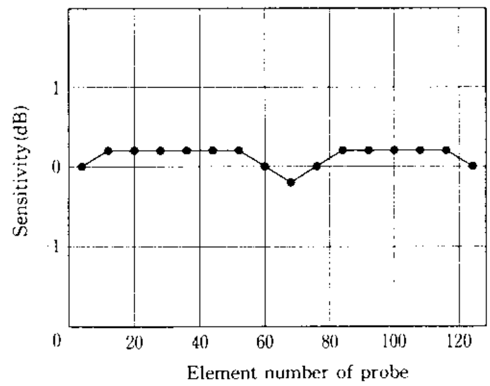

Fig. 7 Distribution of sensitivity in concurrent exitation of 8 elements

probe, with the result shown in **Fig. 6**. The sensitivity difference and phase difference between individual vibrating elements are 1.5 dB maximum and 20 ns maximum, respectively, indicating that vibrating elements with uniform characteristics were obtained. The sensitivity distribution of eight elements concurrently excited and electronically scanning (linear scanning) in units of four elements is shown in **Fig. 7**. A sensitivity distribution as low as 0.4 dB indicates that a high-performance linear array probe had been obtained.

Measurements were also made of the beam profile when a delay time was given to concurrently elements to form a phased array. An example of the result is shown in **Fig. 8**. When given a delay time, the beam profile changes, and by giving an appropriate delay time, a specific beam profile can be obtained.

4.2 Outline of On-line Testing Equipment

Specifications of the materials inspected by the nondestructive inside-surface tester employing the linear array probe are shown in **Table 2**, while the specifications of the tester are shown in **Table 3**. The materials inspected include upset steel pipe, whose wall thickness at the pipe ends is increased, and the dimensions of the materials inspected cover a wide range. The flaw detector has 128-channel transmission and receiver parts to

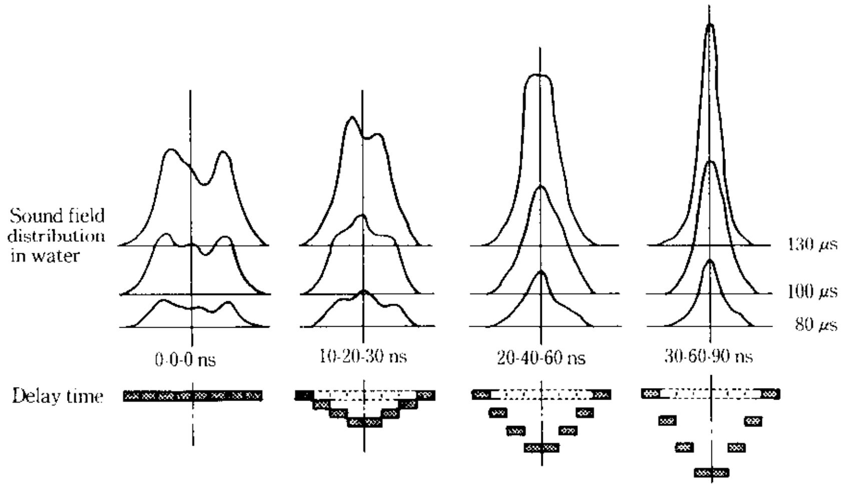

Fig. 8 Ultrasonic sound field distribution by phased array method

Table 2 Conditions of inspection

Material	Seamless tube
Outside diameter	60.3～193.7 mm
Wall thickness	3.0～32.0 mm
Distance of scew	240 mm/rev max.
Rotating speed	1 500 mm/s max.

Table 3 Specifications of on-line tester

Frequency of sensor	5 MHz
Channels of sensor	128 channel
Repeat frequency	18 kHz max.
Amplifier gain	More than 30 dB
Driven element	8 elements at the same time
Delay time between each elements	0～300 ns
Duration of scan	From 1 to 4 elements
Display and presentations	Recorder and cross section profile display

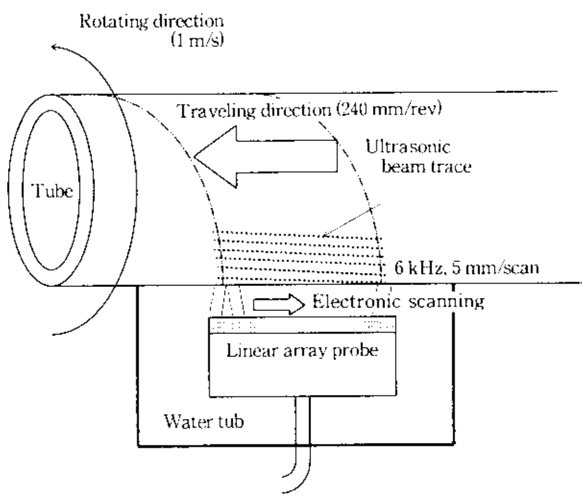

Fig. 9 Schematic structure of on-line apparatus

apply the linear array probe, and a maximum 180-kHz repeat frequency can be obtained to facilitate high-speed scanning. The data processor uses a personal computer and is provided with B-scope and C-scope display functions, as well as binary-coded processing and inversional display functions.

A schematic diagram of the on-line apparatus is shown in **Fig. 9**. The linear array probe is installed in a water bath that can follow the steel pipe being inspected. Rotation and longitudinal movement of the pipe enables flaw detection to be done over the entire surface of the pipe. The water bath can be moved toward or away from the pipe to inspect upset steel pipe, and accurately follows the length of pipe in motion. For this purpose, the water bath is provided with a gimbal mechanism, spring mechanism, and spherical guide roll.

5 Results of the Application to On-line Operation

When applying the non-destructive inside surface tester using the newly developed linear array probe to on-line operation, the scanning pitch of the tester was examined. The results are shown in **Fig. 10**, in which the abscissa represents the repeat frequency, the ordinate represents the duration of scanning in the circumferential direction, and the scanning interval in the longitudinal direction is shown as a parameter. Scanning intervals in the longitudinal direction become integer-multiples of the vibrating element width of the linear array probe. Since the vibrating element width of the newly developed linear array probe is 2 mm, scanning intervals have the values of 2, 4, 6, 8 and 20 mm. These figures indicate that if a repeat frequency of 15 kHz is used, it is possible to obtain a dense scan measuring 4 mm (circumferential direction) × 4 mm (longitudinal direction), even at a circumferential speed of 1 000 mm/s.

An example of the application of the new testing apparatus to on-line operation is shown in **Fig. 11**. This shows an inside surface defect existing in a 13% Cr stainless steel pipe measuring 139.8 mm (out side

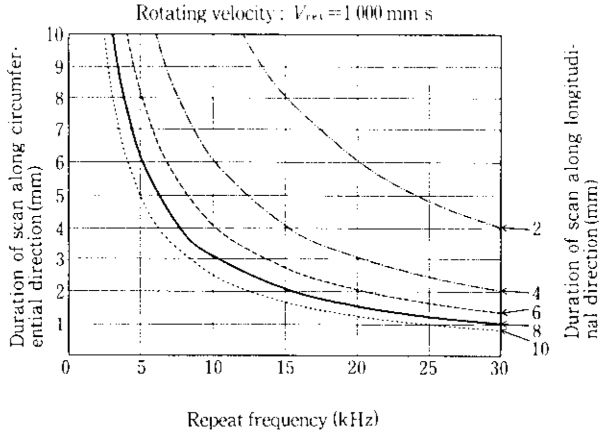

Fig. 10 Relationship between repeat frequency and duration of scan

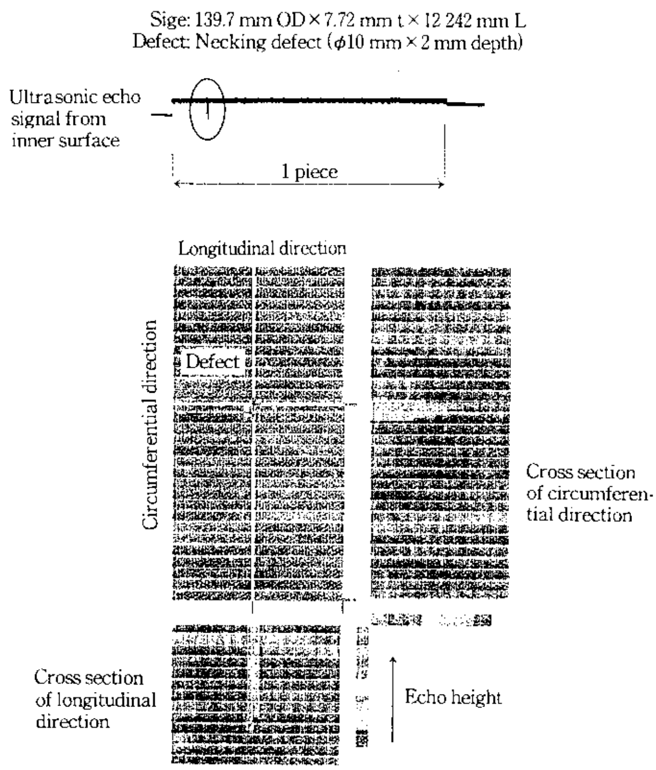

Fig. 11 An example of on-line detection result of necking defect of 13 Cr stainless steel pipe

diameter) × 7.72 mm (wall thickness). At the top is shown an analog chart of the bottom echo, and at the center and bottom are shown the plan and sectional projections of the defect after data processing on the basis of the echo height. The necking defect measures 20 mm (outside diameter) × 1 mm (depth), and was detected with a satisfactory S/N ratio in the analog chart, plan projection, and sectional projection.

6 Conclusions

The authors developed a steel pipe inside-surface non-destructive tester using phased array ultrasonic elements, and introduced the tester into the Small Seamless Pipe Mill[6] of Chita Works. The combined application of this apparatus and the existing ultrasonic non-destructive tester has achieved superior quality assurance of all small-diameter seamless steel pipe. In particular, the application of the phased array ultrasonic elements, which is one of the most up-to-date techniques, to steel pipe inspection has high potential for more perfect and simplified non-destructive tester by further examination in the improvement.

The results obtained by this development are given below.

(1) The phased array ultrasonic transducer has been applied to non-destructive testing in the steel pipe production line successful in practical use.
(2) A steel pipe inside-surface non-destructive flaw detection method and aparatus have been developed which can thereby improving the efficiency for steel pipe inside surface inspection compared with the earlier visual method.
(3) "Size switching free" techniques which can satisfy FMS (flexible manufacturing system) can be easily implemented by taking into consideration the arrangement of the phased array ultrasonic transducer.

The fact that this non-destructive flaw detecting technique employs the binary-coded system to produce the profile suggests the possibility of linking with an intelligent robot which could automatically polish and provide minor repairs to defects in steel materials.

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