Highly Efficient Automatic Ultrasonic Flaw Detection System for Weld Seams of UOE Pipes

Yukinori Iizuka*, Yasuhiro Matsufuji**, Kozo Maeda** and Susumu Iwakura***

* Dr., Senior Research Engineer, Sensing & Control Research Dept., Applied Technology Research Center
** Manager, Process Control Dept., Fukuyama Works
*** Engineer, Welded Pipe Dept., Fukuyama Works

NKK developed a new, automatic ultrasonic flaw detection system for the weld seams of UOE pipes. Features of the new system include (1) two manipulators with up to 20 channels of simultaneous inspection, (2) a highly sensitive detection technique for minute center defects, and (3) a highly accurate seam-tracking sensor. The system is designed to fully meet diverse and strict customer requirements for high-quality products.

1. Introduction

The growing worldwide demand for energy sources such as natural gas has increased the demand for UOE line pipes. Line pipes are used in increasingly severe conditions, and customer quality requirements are becoming more strict. Methods for inspecting the quality of UOE pipes include ultrasonic inspection of base steel plates, ultrasonic or radiographic inspection of weld seams, and ultrasonic or magnetic-particle inspection of pipe ends. Of these, the detection accuracy for ultrasonic inspection of weld seams is the most important component of quality assurance, and customer requirements for this inspection are stringent.

Recently, NKK installed a completely new automatic ultrasonic flaw detection system for weld seams in the welded pipe plant at its Fukuyama Works. A new flaw detection system was designed to fully meet the increasingly diverse and strict customer requirements for product quality, and numerous state-of-the-art technologies were employed.[1)-4)] This paper outlines the newly developed automatic ultrasonic flaw detection system.

2. Outline of system

2.1 Design basis

The welded pipe plant at Fukuyama Works has used a Krautkramer automatic ultrasonic flaw detection system since it was first opened. The previous equipment was a SNUP-type system that performed longitudinal flaw detection, transverse flaw detection, coupling check, and other functions. The same SNUP-type method was adopted for the new system because it has a long, worldwide track record and is highly regarded by our customers. In the specification for the new system, the requirement for the detectability of weld flaws was increased to the highest levels to achieve an extremely functional and accurate flaw detection system.

The objectives established at the start of the project were as follows:

(1) Simultaneous inspection with up to 20 data channels;
(2) Detection of minute center defects using the new channels to allow detection of small areas of incomplete penetration;
(3) Highly accurate seam tracking;
(4) S/N (signal to noise) ratio greater than 10 dB by using dynamic calibration.

Photo 1 and **Fig.1** show the appearance and configuration of the system, respectively, while the specifications are listed in **Table 1**. Detailed descriptions of the specification components follow.

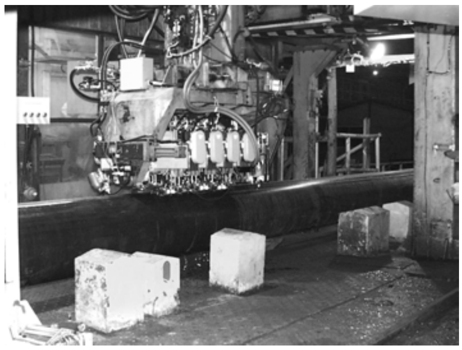

Photo 1 View of the new automatic ultrasonic flaw detection system for weld seams of UOE pipes

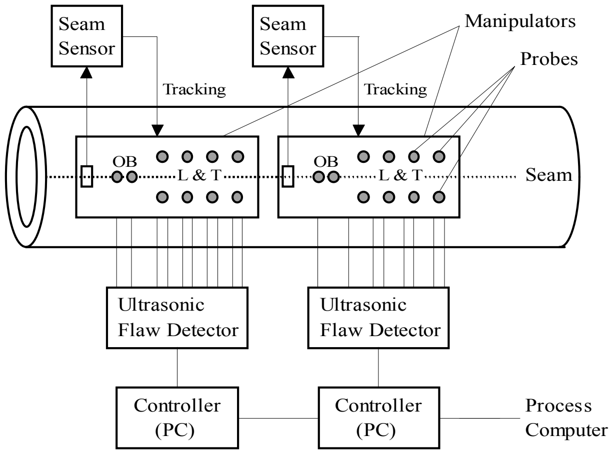

Fig.1 Configuration of the system

Table 1 System specifications

Item	Specification
Pipe size	Diameter : 400mm～1422mm Thickness : 6.4mm～50.8mm Length : 5.5m～19m
Line speed	1mpm～30mpm
Inspection method	Pulse reflection method Single probe technique Double probe technique
Pulser & receiver (Krautkramer)	0.5MHz～10MHz/-3dB Max. gain : 100dB PRF 1kHz/ch
Test frequency	4MHz
Number of channel	L&T : max. 16ch OB : max. 4ch
Probe: Transducer / Size / Angle of refraction / Inclination to weld axis	Composite type L&T: 8mm×9mm OB : 10mm L&T : 65deg.～75deg. OB : 45deg. L : 90deg. T : 45deg.
Detectability	φ 1.6mm drilled hole
Pulse pitch	0.166mm/pulse at 10mpm
Coupling method	L,T : Water gap (0.5mm) OB : Water column (40mm)
Coupling check	Pulse reflection method AGC available
Seam tracking	Eddy current method ±1mm

2.2 Flaw detection method

The pulse-echo flaw detection method using angle-beam probes was adopted. This is the most commonly used method for automatic inspection of weld seams. In the new design, the positions of the probes are fixed, while the pipes move beneath them. The flaw detector uses synchronous averaging[1)] and chirp pulse compression[2)] technologies, which were developed by NKK, to obtain a high S/N ratio.

2.3 Probes

Longitudinal (L), transverse (T), and on-bead (OB) probes are mounted on the two manipulators, as shown in **Fig.1**. The L and T probes can use up to 16 channels, while the OB probes use a maximum of 4 channels. The distance from the weld line can be changed for each of the L and T probes to adjust the skip point. The probe positions are automatically set by entering the outer diameter and thickness of the pipe, the angle of refraction, and the skip distance into the controller PC.

The angle of refraction is determined from the outer diameter and thickness of the pipe and is set by changing the probes. Generally, the angle is from 60° to 70° for L and T flaw detection of the inside and outside surfaces, and 45° for OB flaw detection. The angle can be increased to approximately 83° for detecting minute center defects. This method for detecting minute center defects was newly developed for this system[3)].

Because the system has two manipulators, the positions of the probes can be flexibly arranged to satisfy various customer inspection specifications. When only one manipulator is needed for flaw detection, the other is in standby and can be set and calibrated for the next lot of pipes. This allows inspection of the next lot without losing time for resetting and readjusting. **Fig.2** shows examples of some probe arrangements.

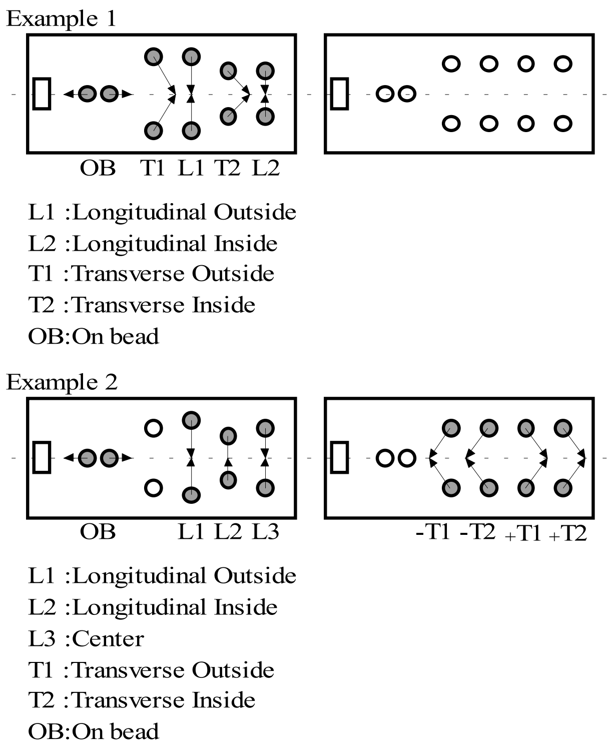

Fig.2 Examples of probe arrangements

2.4 Coupling

The L and T probes use the gap coupling method, while the water-column coupling method is used for the OB probes.

The L and T probes have built-in normal beam probes for verifying the adequacy of coupling. For the OB probe, a pair of probes is positioned face to face so that these flaw detection probes can also carry out coupling checks. Each channel carries out a coupling check before performing angle flaw detection. An alarm is activated when a coupling failure is detected.

2.5 Adjustment and calibration of flaw detection system

The flaw detection system has the functions to preset the probe and gate positions, to automatically set the gate, and to automatically calibrate the gain to ensure that the adjustments and calibrations are properly performed.

For example, artificial flaws at the center and both ends of the bead are used to automatically set the gate for L flaw detection. The positions and widths of the flaw detection gates are automatically set so that the echoes from all the artificial flaws can be detected. The system determines the proper setting for the flaw detection gates across the entire width of the weld seam.

The automatic gain calibration function automatically sets the gain so that the echo heights of the artificial flaws on the calibration sample are equal to the target values.

2.6 Seam tracking

To achieve reliable flaw detection, the probes must accurately detect and track the center of the weld seam of the moving pipe. Therefore, a new, highly accurate seam-tracking sensor was developed for this system[4]. The new seam-tracking sensor uses the eddy-current method to detect the bead center.

2.7 Ultrasonic beam pass drawing function

The controller PC for this flaw detection system has a ultrasonic beam pass drawing function to ensure that the ultrasonic beams are oriented to provide optimum flaw detection under various conditions. The transmission paths of the ultrasonic beams are easily visualized by dragging the incident point on the screen. **Fig.3** shows an example of a screen display.

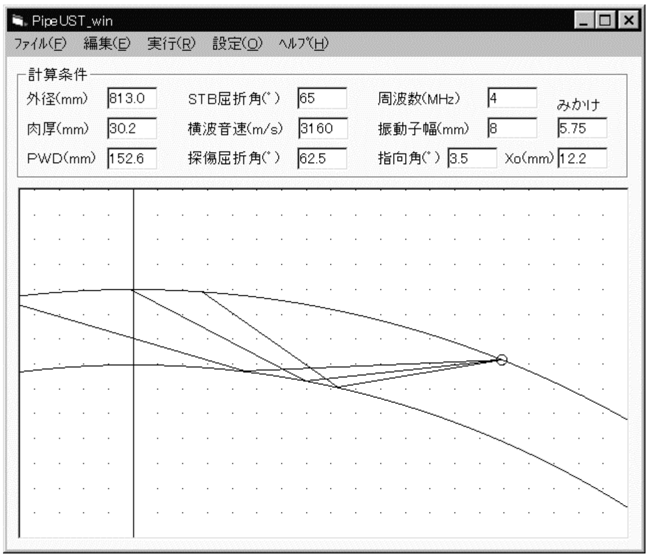

Fig.3 Ultrasonic beam path display

3. Technologies for improving detectability

Major new technologies that were adopted to improve flaw detectability using this system are as follows:

(1) Chirp pulse compression for increasing the S/N ratio;

(2) Normal incident beam method for inspecting minute center defects;

(3) Highly accurate seam-tracking sensor.

3.1 Chirp pulse compression method

Conventional ultrasonic flaw detection systems generally use impulse-type spike pulses for the input signals. The advantage of this method is the excellent time resolution of the echo. However, this method needs a high voltage to provide a high S/N ratio in an environment that is full of nearby noise sources, such as in on-line flaw detection. Unfortunately, voltage levels the probes and circuits can withstand are limited. One alternative to increasing the voltage is to use a signal that has a large average power over a long duration of time, such as a tone-burst pulse (a few cycles of sine waves). However, this method reduces the time resolution. In contrast, pulse compression technology is an established method that uses input signals with a long time duration, while providing a high time resolution. Real-time digital signal processing technology was developed to apply this method to ultrasonic flaw detection[2].

Fig.4 explains the chirp pulse compression principle. The input signal is a frequency-sweeping chirp pulse. The pulse width of the received signal remains large, as shown in the figure. This received signal passes through the pulse compression filter, which is designed to provide an impulse response with a delay characteristic that is opposite to that of the input signal. The echo signal, which is widely spread over the time domain, gathers at a single point as it passes through the pulse compression filter. This increases the amplitude while decreasing the pulse width; in other words, the pulse is compressed. Because the waveforms of the electrical noise are not correlated to those of the input signal, the noise levels remain low, which significantly improves the S/N ratio.

The pulse compression filter uses the cross correlation between FIR (Finite Impulse Response) filter elements. The relation between the input signal $S_t\ (t)$, the impulse response of the probe $f\ (t)$, the received signal $S_r\ (t)$, and the signal after pulse compression $S_c\ (t)$ is expressed in the frequency domain as follows:

$$\begin{aligned} S_{c(j\omega)} &= S_t^{\,*}{}_{(j\omega)} \cdot S_{r(j\omega)} \\ &= S_t^{\,*}{}_{(j\omega)} \cdot F_{(j\omega)} \cdot S_{t(j\omega)} \\ &= S_t^{\,*}{}_{(j\omega)} \cdot S_{t(j\omega)} \cdot F_{(j\omega)} \end{aligned} \quad \cdots\cdots(1)$$

Where * means a complex conjugate. Equation (1) shows that the waveform of the compressed echo is equivalent to the case where the auto-correlation function $S_t^{*}{}_{(j\omega)} \cdot S_{t\ (j\omega)}$ of the chirp pulse $S_t\ (t)$ is used as the input pulse. This means that an ultrasonic flaw detection system using chirp pulse compression is equivalent to that using the auto-correlation function of the chirp pulse in place of the conventional spike pulse. **Fig.5** illustrates the waveforms and spectra of the auto-correlation function of the chirp pulse and the conventional spike pulse. The auto-correlation function of the chirp pulse has a waveform with a controlled center frequency and bandwidth. This function provides a beam profile and distance-amplitude characteristic with channel-to-channel variations that are less than those of the spike pulse.

This technology improved the S/N ratio by about 20 dB. Further, the use of synchronous averaging processing, which has proven performance in the ultrasonic flaw detection of electric-resistance-welded pipe seams, makes the new flaw detection system almost noiseless with regard to electrical noise.

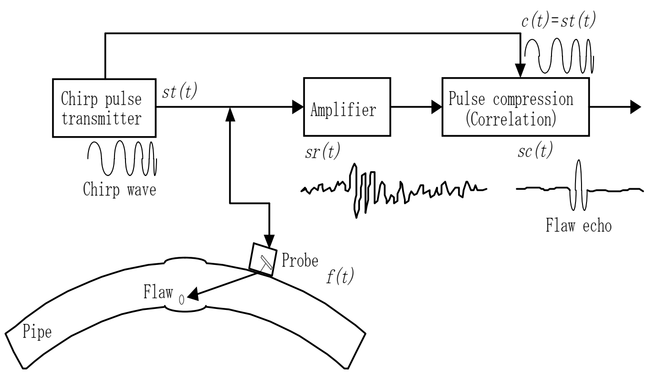

Fig.4 Principle of chirp pulse compression

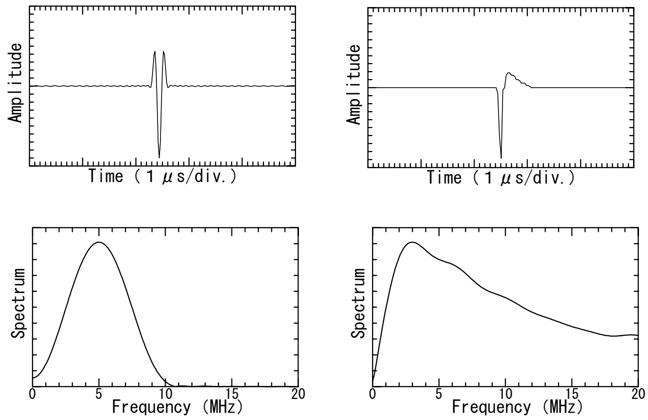

Fig. 5 Examples of the auto-correlation function for the chirp pulse and the conventional spike pulse

3.2 Normal incident beam flaw detection method

Conventional angle-beam flaw detection uses refraction angles between 60° and 70°. The skip is set at 0.25 or 0.75 for detecting minute center defects. These conditions result in an oblique incidence angle for flat defects such as incomplete penetration. Thus, the detection sensitivity for conventional angle-beam flaw detection methods is unfavorable, so a new, high sensitivity technique was developed to inspect flat defects in the thick center part of weld seams.

The incident beam normal to these defects produces a regular-reflection echo, while the echo from the weld bead is kept small, as shown in **Fig.6**. This allows defects to be detected with a high S/N ratio. This flaw detection method uses a probe with an angle of refraction defined by Equation (2) at a distance from the weld line defined by Equation (3).

$$\theta = \sin^{-1}\left(1 - \frac{t}{D}\right) \quad \cdots\cdots(2)$$

$$PWD = \left(\frac{\pi}{2} - \theta\right) \cdot \frac{D}{2} \quad \cdots\cdots(3)$$

However, Equation (2) indicates that the angle of refraction exceeds 70° when t/D is less than 6%. For example, when *t*/*D* is 1%, an angle of refraction as large as 82° is required. The angle of refraction for the conventional angle-beam method is generally smaller than 70°. At angles of refraction greater than 70°, the sensitivity decreases markedly because the echo transmittance of sound pressure drops significantly and also because the virtual probe size becomes small. This makes the system easily affected by external electric noise. Therefore, the chirp pulse compression method described above was adopted to increase the S/N ratio, resulting in an effective, on-line, normal incident beam, flaw detection method.

A large number of probes with slightly different angles of refraction are needed to meet the condition for normal incidence, and conditions required for normal incidence may not be achievable for some actual inspection conditions. To solve these problems, a mechanism for fine-tuning the angle of incidence was added to the system, and the directivity beam spread of the probe was appropriately designed.

On-line experiments confirmed that this technique can detect minute defects equivalent to a square flat defect of 1×1 mm.

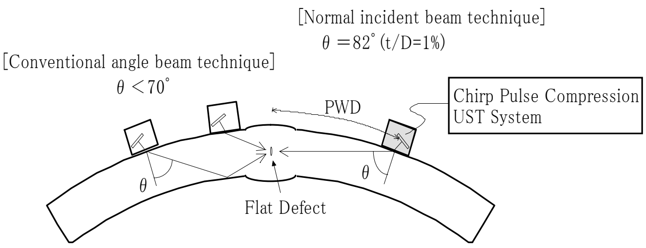

Fig.6 Configuration of the new angle beam testing technique

3.3 Highly accurate seam-tracking sensor

Conventional eddy current seam-tracking sensors have two eddy current sensors placed at fixed distances from the pipe above the weld seam. Displacement from the seam is detected by observing whether the differential output of the two eddy-current sensors is plus or minus. Lift-off variations due to the pipe size and bead shape affect the accuracy of this system. A new seam-tracking sensor was developed to solve these problems[4].

Fig.7 shows the configuration of the new seam-tracking sensor. The shape of the eddy current sensor is unique. The primary coils are wound on two legs of the E-shaped ferrite core so that crossing magnetic fluxes with opposite directions are generated in the center core when AC current is supplied to the primary coils. The secondary coil wound on the center core detects changes in the magnetic flux. This eddy-current sensor acts as a spatial differential sensor by itself.

The E-shaped eddy-current sensor is placed below a turning disk that rotates at 3 r/s. Since this eddy-current sensor acts as a differential sensor, as mentioned above, two peak signals with different polarities appear when it passes the left and right shoulders of the weld bead. Further, two photoelectric sensors are placed above the turning disk and the position of the eddy-current sensor is marked by a black line. In this way, the point in time when the eddy-current sensor passes the positions of the photoelectric sensors is detected.

Processing of these four timing signals not only determines whether the centerline of the weld seam is to the left or right of the rotation axis of the eddy-current sensor, but also provides the displacement distance. Since this method uses the timing of the peak signal output from the eddy-current sensor, the dimensions of the pipe and bead shape do not affect the results like they do with a conventional sensor. This displacement information from the sensor is used to keep the manipulator above the center of the weld.

On-line experiments proved that this seam-tracking sensor can track weld seams with an accuracy of ±1mm.

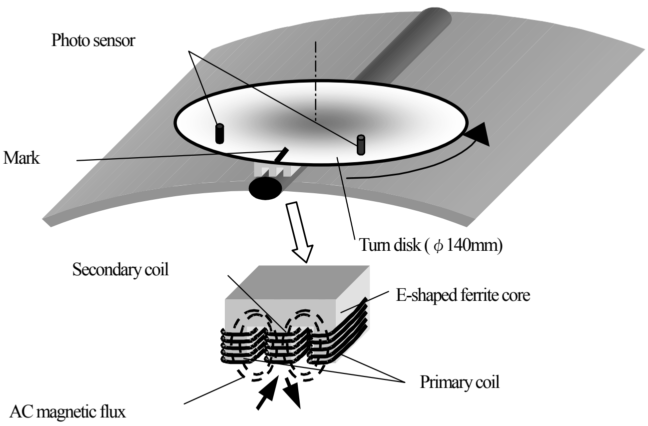

Fig.7 Principle of the seam-tracking sensor

4. Example of flaw detection

Fig.8 illustrates the results of a flaw detection test using a sample pipe with artificial defects. The sample pipe was 813.0 mm in diameter and 80.2 mm thick. The L1, L2, and L3 probes were aimed at the outside, inside, and thick center area, respectively. The L1 and L2 beams were aimed at the 5% notch, while L3 was aimed at the φ3 mm side-drilled hole.

Fig.8 confirms the detection of all the artificial defects in the sample pipe, including not only those in the weld, but also defects in the zones neighboring the weld. The S/N ratios were very high, as shown in **Table 2**. The S/N ratios for the φ1.6 mm drilled hole exceeded 10 dB for L1, L2, and L3.

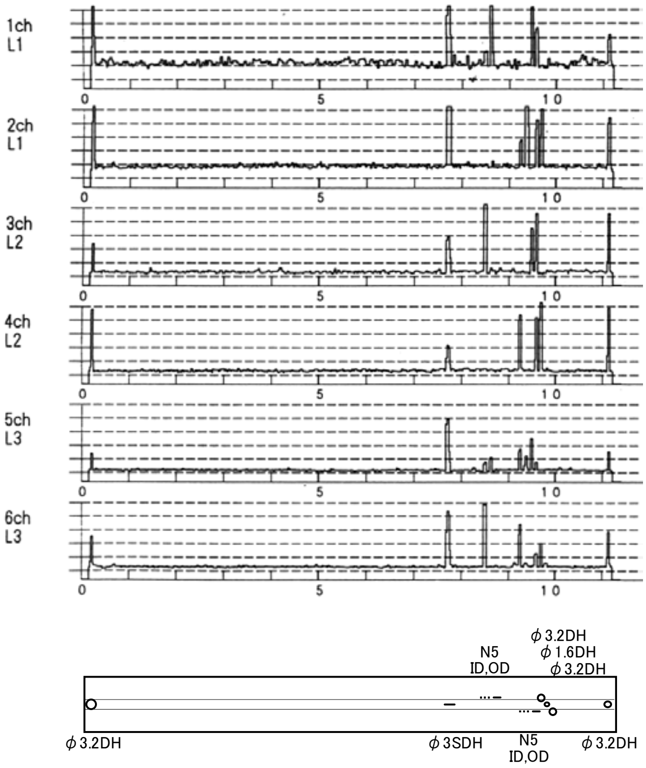

Fig.8 Results of dynamic test

Table 2 Results of dynamic test

Channel	Artificial defect	Signal	Noise	S/N
L1(OD)	N5OD	127%	30%	12.5dB
	ϕ 1.6DH	85%	25%	10.6dB
L2(ID)	N5ID	127%	10%	22.1dB
	ϕ 1.6DH	92%	8%	21.2dB
L3(Center)	ϕ 3SDH	89%	6%	23.4dB
	ϕ 1.6DH	26%	6%	12.7dB

5. Conclusion

The automatic, ultrasonic, weld seam flaw detection system recently installed in NKK's Fukuyama Pipe Mill is the newest and most advanced system that was developed by integrating NKK's expertise in nondestructive testing technologies. This system can meet a wide range of requirements for ultrasonic flaw detection. The capabilities of the system give us confidence that we can supply high-quality products that meet our customers' requirements.

References

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Yukinori Iizuka
Sensing & Control Research Dept., Applied Technology Research Center
Tel : (81) 44-322-6289
E-mail : iizuka@lab.keihin.nkk.co.jp
Yasuhiro Matsufuji
Process Control Dept., Fukuyama Works
Tel : (81) 84-945-3327
E-mail : Yasuhiro_Matsufuji@ntsgw.tokyo.nkk.co.jp