JFE TECHNICAL REPORT
No. 7 (Jan. 2006)

NDI Techniques Supporting Steel Pipe Products†

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Abstract:

This paper describes JFE original ultrasonic testing (UT) technologies in Non-destructive inspection (NDI) systems that assure quality of JFE Steel pipe products. To enhance signal-to-noise ratio of UT, the high-speed digital signal processing techniques of synchronous averaging and chirp pulse compression have been developed and installed in ultrasonic flaw detectors of welding pipe. In order to improve detectability of flaws located at middle of wall thickness of weld, the normal incident beam technique for UOE pipe and the multi-probe technique for ERW pipe have been developed respectively. The analysis technique of ultrasonic field and that of ultrasonic wave propagation are applied as basic technology for the developments.

1. Introduction

Nondestructive inspection (NDI) technology is a core technology for inspection/quality assurance of steel pipe products. It also plays an indispensable role as a quality measurement method in process control for stable production of high quality products. JFE Steel therefore assigned NDI technology a position as a critical technologies from an early date, and has carried out development to improve NDI performance and introduced the advanced NDI technologies. In particular, in recent years, users' inspection needs have become increasing strict due to the diversification of steel pipe products and expanded range of applications, and at the same time, heightened requirements have been placed on quality measurement accompanying the use of more advanced production processes. JFE Steel has responded to these challenges by further strengthening its outstanding development system.

This paper describes original high accuracy, high reliability NDI technologies developed to date by JFE Steel and JFE R&D, with special emphasis on the company's ultrasonic testing (UT) technologies.

2. Digital Signal Process Technique for UT

2.1 Background of Development

Ultrasonic testing makes it possible to detect flaws from the material surface to internal flaws and is widely used in inspections of iron and steel products as one of the most important NDI techniques. In the field of steel pipes, on-line inspections over the full length of all products are performed using UT.

Detectability in UT inspections is mainly determined by the frequency and beam size of the UT signal, the microstructure of the material being inspected, the noise environment, and the sensitivity setting of the device. Among these, the specification design of the ultrasonic transducer, which determines frequency and beam size, is naturally the most important technical point. (Note: In the following, transducer is used when referring to performance, and probe when referring to the hardware.) To further improve performance, the authors developed the real time digital signal processing techniques of synchronous averaging and chirp pulse compression as techniques for improving the signal-to-noise ratio (S/N) of UT signals[1,2].

Figure 1 shows an example of the noise factors in UT. Various factors such as electric noise and echo noise exist, and these frequently occur in combination. Conventional methods of improving S/N included strengthening the shielding and grounding of the signal line, treatment of water adhering to the pipe, and others, but

† Originally published in *JFE GIHO* No. 9 (Aug 2005), p. 40–45

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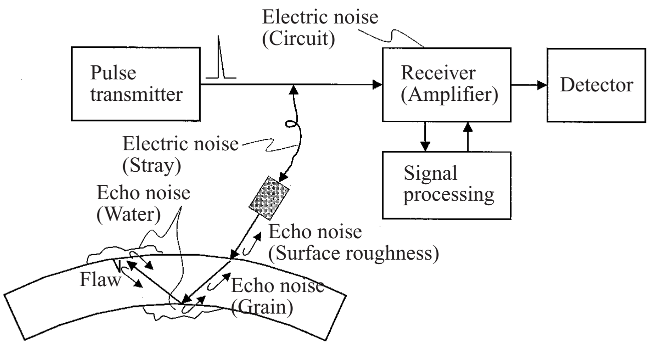

Fig. 1 The cause of noises in UT

their effects were limited to individual factors. In contrast, as features of JFE Steel's digital signal processing techniques, these techniques are effective against various kinds of noise because processing is based on the properties of noise as such, and they can be applied in addition to the conventional measures.

2.2 Outline of Signal Processing Techniques

2.2.1 Synchronous averaging

Figure 2 shows the principle of synchronous averaging. Focusing on the cyclical nature of UT signals, signals repeated a certain number of times are averaged in synchronization with the transmitted wave. This makes it possible to reduce noise such as the waveform

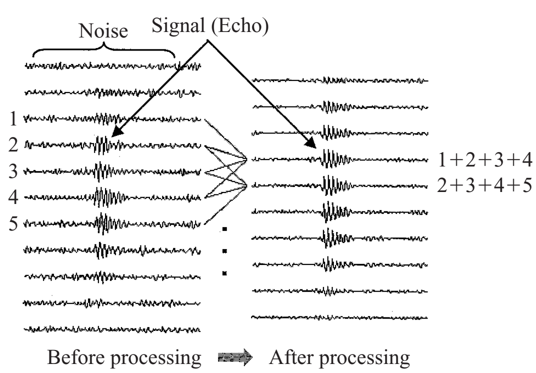

Fig. 2 Principle of the synchronous averaging

changes which occur during repetition of the UT signal. Thus, as a feature of this technique, it is possible to reduce not only random electric noise, but also echo noise caused by water adhering to the object of measurement and air bubbles in the water for acoustic coupling.

As the amount of improvement in S/N, when N_a is the average number of signals, $20\log N_a$(dB) can be obtained with single-burst noise, and $20\log\sqrt{N_a}$(dB) can be obtained with Gaussian random noise. Because this processing is applied only to the reflected wave, it can easily be introduced in existing flaw detection systems.

2.2.2 Chirp pulse compression

Figure 3 shows the principle of chirp pulse compression. A long burst signal (chirp) in the time-domain, which is allowed to sweep the frequency, is used in the transmitted wave. When the signal is passed through a pulse compression filter having frequency-delay characteristics which are the reverse of those of the transmitted wave during receiving, the echo which had spread along the time-domain is concentrated at one position, resulting in an increase in amplitude together with tight compression of the pulse width. Because the burst signal has high average electric power, an effect equivalent to that when a short, large transmitted wave is used can be obtained with this pulse compression technique. At the same time, S/N is greatly improved for noise factors having no correlation to the chirp waveform because pulse compression has no effect on these kinds of noise and their level remains low.

Actual S/N improvement is determined by the waveform of the chirp wave and the frequency characteristics of the transducer, but normally, an improvement on the order of 10–20 dB can be obtained[2]. Particularly large improvement of S/N can be expected with electric noise with this technique.

2.2.3 Key points in practical application of signal processing

Although the signal processing techniques

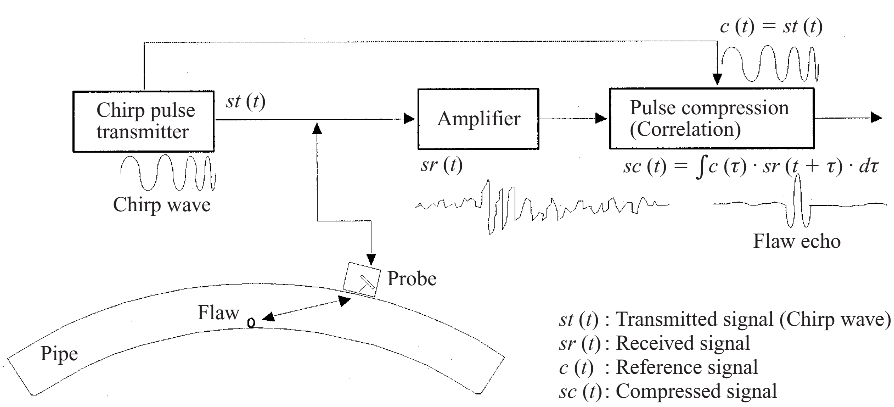

Fig. 3 Principle of the chirp pulse compression

described above had long been known in rader and certain other fields, to apply in practical UT application, the development of high speed digital signal processing technique for accurate calculation was technical problem. Because, with UT signals, processing at the mega hertz order is necessary since the band width-center frequency ratio is extremely wide, and processing within 1msec is required for on-line inspection.

For this, the authors developed a hardware technology which completes computational processing in one-pulse units, utilizing the unoccupied time in the ultrasonic wave pulse cycle[3]. They also developed an application technology for optimizing signal processing parameters for respective UT applications. As a result, JFE Steel realized practical application of digital signal processing of on-line UT signals for the first time in the world[4,5].

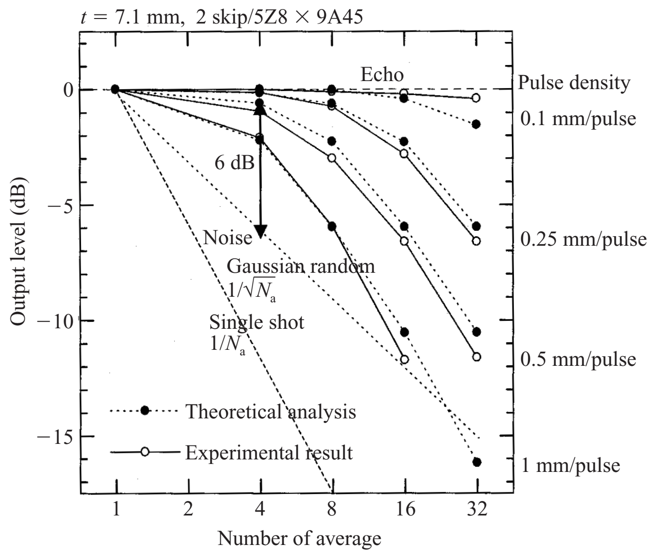

Fig. 5 Relationship between average and output level of the synchronous averaging

2.3 Examples of Application

2.3.1 Improvement of *S*/*N* in seam UT of ERW pipes by synchronous averaging

Seam UT of electric resistance welded (ERW) pipes is a flaw detection system for inspection of the weld, which is the most important part of the product from the viewpoint of quality, and is applied after welding and after hydrostatic testing. Synchronous averaging was extremely effective for further improvement of *S*/*N* in these seam UT inspections.

Figure 4 shows an example of ERW seam UT. The seam section from the inner surface to the outer surface is targeted with a multi-channel angle beam probe, and the seam is inspected in the longitudinal direction by moving the pipe or the probe in the pipe axial direction.

When synchronous averaging is performed on this UT signal, the output displays characteristics like those in **Fig. 5**. That is, although noise is reduced monotonously as the average number of signals increases, there is virtually no reduction in the flaw echo up to a certain number of signals. This is because the echo appears over a number of signals as the flaw is passing through the beam width. As a result of this feature, it is possible to improve *S*/*N* by specifying the optimum average number of signals corresponding to the pulse density. For example, with a pulse density of 0.5 mm per pulse, the optimum average number of signals is 4 and an *S*/*N* improvement of 6 dB with respect to Gaussian random noise can be obtained. Converted to flaw area, this value is equivalent to detection at one-half the former level.

To date, the effect of this technique in reducing electric noise from welders and annealers and reducing echo noise from water adhering to the inner and outer surfaces of pipes has been confirmed[6], and the technique is now contributing to high UT sensitivity and reduction of false indications in seam UT at JFE Steel East Japan Works' Keihin and Chita Works' pipe mills.

2.3.2 High sensitivity seam UT for UOE pipe by chirp pulse compression

With UOE pipe, as with ERW pipe, welds are inspected by seam UT after welding and after expanding and hydrostatic testing. In this type of seam UT, a channel for a normal incident beam technique, which is

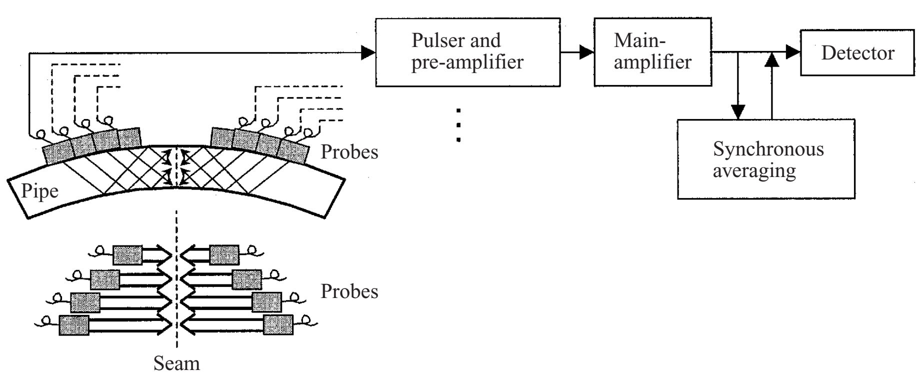

Fig. 4 Example of seam-UT system applied to ERW steel pipe

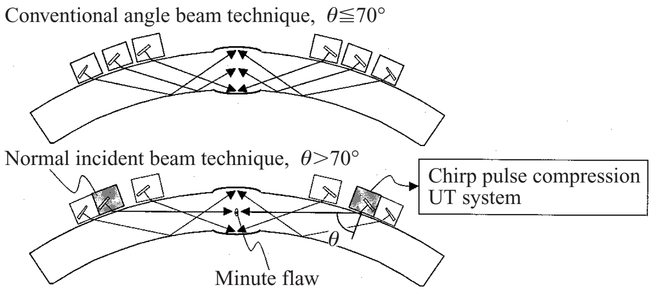

Fig. 6 New angle beam testing technique for UOE steel pipes

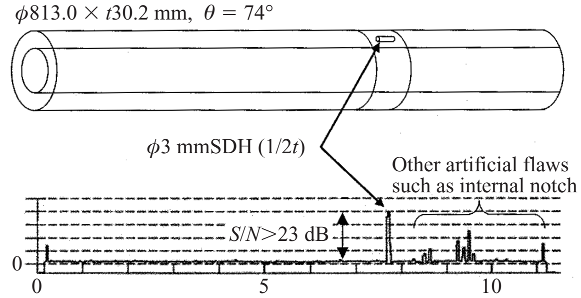

Fig. 7 Result of side drilled hole detection by normal incident beam technique

based on a new concept, has been added to enhance the flaw detection output in the pipe wall center-of-thickness area and expand the range of weld coverage[7)].

The probe arrangement in this normal incident beam technique is shown in **Fig. 6** in comparison with the conventional technique. The upper part of the figure shows the arrangement in conventional angle beam testing, where a beam angle on the order of 60–70° is used, depending on the groove angle. This beam angle is not necessarily optimal for inspection of the center of thickness, as the incident beam is inclined relative to the center of thickness. Tandem probe inspection is the general practice for inspecting the center of thickness, but when applied to UOE pipe, it is not possible to arrange a probe at the 0.25 skip position due to interference with the bead, and if the probes are positioned at the 0.75 skip and 1.25 skip positions, the beam path length becomes excessive and *S*/*N* deteriorates. Moreover, the 45° multi-probe tandem method, which is discussed later in this paper, has the problem of tending to detect echoes from the bead, and with the tandem method using only two 45° angle probes, coverage is limited to the area where the beams intersect.

On the other hand, with the normal incident beam technique shown in the lower part of Fig. 6, the ultrasonic beam is incident in the normal direction (90°) relative to the center of thickness. As a result, this technique has the following features: (1) High detection capacity for small planar flaws in the center of thickness, (2) wide coverage because the beam is incident on the entire weld, and (3) low susceptibility to the influence of echoes from the bead because the beam is incident at a very shallow angle relative to the bead.

Nevertheless, this flaw detection technique had not been applied practically in the past. This was because a large beam angle from 75° to 83° is required to satisfy the conditions for a normal incident beam with objects the size of UOE pipe. With beam angles this large, sensitivity is reduced markedly as a result of reduced echo transmittance of sound pressure and increased divergence loss caused by reduction in the height of the virtual transducer, and electric noise also increases in on-line flaw detection. Considering these problems, the common sense until now had been that the applicable range of beam angles was no more than 70°.

In contrast, JFE Steel and JFE R&D realized practical application of the normal incident beam technique by applying chirp pulse compression to reduce electric noise and designing the transducer height so as to achieve an appropriate beam spread. **Figure 7** shows an example of the flaw detection results with this technique. In this example, a ϕ3 mm side-drilled hole at the center of thickness was detected with $S/N = 23$ dB. When this result is converted to the detection capacity with a square planar flaw by calculating the reflection coefficient of sound pressure for various kinds of flaws, it corresponds to a level enabling detection of a 1 mm^2 flaw.

In seam UT of UOE pipe at West Japan Works (Fukuyama District), in addition to the normal incident beam channel discussed above, chirp pulse compression and synchronous averaging have also been installed in all channels, and the detection capability has won a high evaluation from customers.

3. Multi-probe UT Technique for ERW Pipe

3.1 Background of Development

The 26” medium diameter ERW pipe mill at JFE Steel’s Chita Works is capable of producing heavy-walled products with thicknesses up to 25.4 mm. For quality assurance of these thick welds, a multi-probe UT technique which can cover the full weld cross-section with a high detection capacity was introduced[8,9)].

In seam UT of ERW pipe, the general practice for coverage of the full cross section of welds until now was a single probe technique using a probe arrangement of the type shown previously in Fig. 4. With this arrangement, the beam is incident at an inclined angle relative to flaws in the center of thickness. With thin materials, inspection by the single probe technique is possible by setting a higher sensitivity because corner reflections form in the range of beam spread. However, when the material thickness exceeds 20 mm, it becomes difficult for echoes from flaws in the center of thickness to reach the same probe as that which transmitted the signal, and an extreme increase in sensitivity becomes necessary. This invites problems such as false indications and is undesirable from the viewpoint of operation.

In contrast, the multi-probe UT technique was developed to enable tandem probe inspection simultaneously with all channels using angles probes arranged continuously with 8 channels on one side, and is a flaw detection technique which possesses a high detection capacity for flaws in the center of thickness, and at the same time, has the feature of high stability with respect to deviation in the seam position.

3.2 Principle of Full-thickness Inspection by Multi-probe Technique

The probe arrangement used with this technique is shown in **Fig. 8**. Eight 45° angle probes are arranged respectively on each of the two sides of the weld. The fact that these eight units on one side perform simultaneous transmitting-simultaneous signal receiving is the key point of this technique, as this allows not only single probe inspection, but also tandem probe inspection using all probes in combination. For example, when a flaw is located in the center of thickness, the ultrasonic beam travels by the route shown at center right in the figure, and the echo is detected as a flaw by the tandem probe technique. On the other hand, when the flaw is at the outer surface, the beam follows the route shown at center left, and the echo is detected by the single probe technique.

Figure 9 shows the result when this multi-probe system was scanned in the pipe circumferential direction and the echo profiles obtained by the single probe technique with each of the probes were synthesized. The flaw was a notch on the outside of the pipe. It can be understood that inspection of the full cross section of

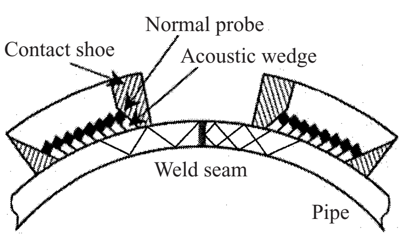

Fig. 8 Probe layout of the multi-probe UT for ERW steel pipe

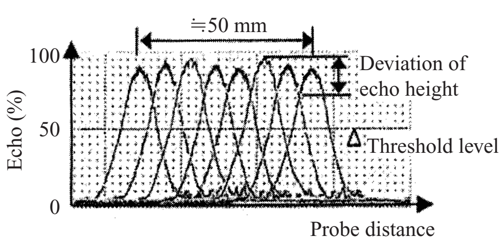

Fig. 9 Echo profile of the multi-probe

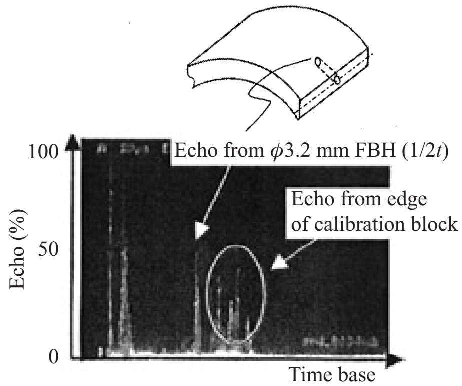

Fig. 10 Detection of a flat bottom hole located at middle of wall thickness for calibration

the pipe thickness is possible because the beams of the individual probes have been designed to overlap within the effective beam width.

3.3 Examples of Calibration Data

The artificial flaws used in calibrations with this technique include not only conventional artificial flaws such as ϕ3.2 mm drilled holes and 5% notches on the inner and outer surfaces, but also a ϕ3.2 mm flat bottom hole machined perpendicular to the seam at the center of thickness. Reflectgrams for detection of these artificial flaws are shown in **Fig. 10**. As can be understood from this figure, center-of-thickness flaws, which are difficult to detect with the conventional 45° single probe technique, can be detected with high *S/N* using the tandem probe technique.

Because this technique also demonstrates high robustness with respect to seam position deviations, it has earned a high evaluation from users and is contributing to improved reliability in ERW linepipe.

4. UT Analysis Techniques

Ultrasonic testing analysis techniques play an essential role as a base for all of the UT techniques described above. The following presents examples of JFE R&D's UT analysis techniques.

(1) Ultrasonic Field Analysis

In setting the pulse density and distance between ultrasonic transducers, a knowledge of the effective beam width is indispensable. The effective beam width is also necessary because the optimum average number of signals is theoretically required for synchronous averaging, as described in Chapter 2[1].

Field analysis based on Huygen's theorem is performed as a method of calculating this beam width. In this method, the sound pressure at arbitrary points is calculated by superposition of the spherical waves from a finely-segmented transducer. **Figure 11** shows an example of a calculation. Because this type of

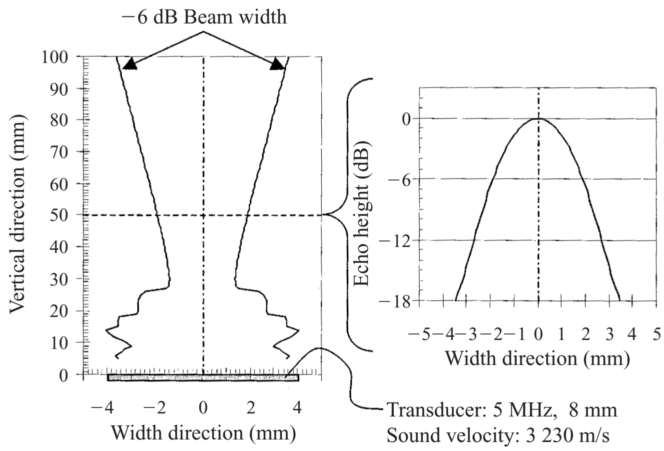

Fig. 11 Calculation result of ultrasonic field analysis

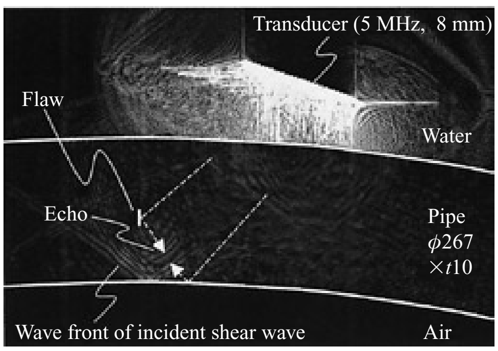

Fig. 12 Calculation result of ultrasonic propagation analysis

calculation can be performed within several seconds for any desired transducer, including the focus type, and for the speed of sound in various media, it has become an extremely effective tool for analytical studies of effective beam width. This analysis technique has also been used in the design of phased array transducers and in studies of side lobe.

(2) Ultrasonic Propagation Analysis

Analysis of how ultrasonic waves propagate in objects under inspection is important for understanding UT beam reflection behavior/mode conversion in flaws and in investigating the causes of echo noise and studying the optimum incident position.

Ultrasonic propagation analysis by calculus of finite differences is performed for these types of analyses. In this method, an elastic wave equation is approximated by calculus of finite differences, and the condition of the propagating wave is calculated successively. **Figure 12** is an example of a calculation. The figure shows the condition of a corner reflection formed during inspection of thin material in flaw detection of the center of thickness of a steel pipe by the 45° angle probe technique. Because it is possible to specify multiple and arbitrarily-shaped media, as illustrated here, this analytical technique is actively used in optimizing inspection techniques and analyzing inspection results.

5. Conclusion

Among the various NDI techniques which support steel pipe products at JFE Steel, this paper has described several original advanced NDI techniques developed by JFE itself, including digital signal processing techniques for UT, multi-probe tandem UT, and UT analysis techniques.

In the future, JFE Steel will continue to develop more advanced NDI techniques as it strives to improve the quality of steel pipe products.

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