NIPPON STEEL TECHNICAL REPORT No. 89 JANUARY 2004

UDC 620 . 179 . 16

Performance Enhancement of On-line Lamb Wave Inspection System Using SSP Technique

Yasuaki NAGATA[*1]
Syuji NAITO[*2]
Toshiharu KINO[*3]
Jun HIROWATARI[*3]
Yusuke KONNO[*1]
Mitsutoshi KUBOTA[*3]
Osamu SEKIGUCHI[*3]

Abstract

In order to improve the defect detectability of Lamb wave inspection system conventionally used for on-line detection of internal defects of steel strip, application of non-linear signal processing, SSP (split spectrum processing), to Lamb waves and the optimization of the SSP parameters were investigated. Sample strips with natural defects were used to evaluate the performance of SSP in this research. As a result, the improvement of the sensitivity of Lamb wave inspection was confirmed by optimum selection of SSP parameters. Furthermore, real-time processing of SSP was realized. Consequently, the newly developed Lamb wave can perform SSP at a 500 Hz repetition rate that is sufficiently high repetition rate for the on-line Lamb wave inspection system.

1. Introduction

A Lamb wave inspection system using a wheel type probe has long been used for the detection of internal defects of steel strips, such as air bubbles and nonmetallic inclusions. This system is a device that generates Lamb waves in the width direction of a steel strip when ultrasonic waves were projected diagonally to the steel strip with a probe enclosed in a wheel, and detects the defects by receiving reflected signals from the defects. The Lamb wave inspection system now in online use detects using narrow-band toneburst waves of several MHz. The use of those narrow-band ultrasonic waves is intended to enhance defect detectability by using only Lamb waves of specific frequency in specific mode so that the influence of the velocity dispersiveness of Lamb waves can be eliminated.

The defect detectability of an online device is influenced to a greater extent by the grain noise produced by the echo reflected from the grain boundary as well as by electric noise. Of the two, the electric noise can be removed by a software or hardware filter, whereas the grain noise is an intrinsic one generated when ultrasonic waves spread inside the steel strips. Since the Lamb wave inspection system uses narrow-band toneburst waves, it is possible to reduce grain noise and electric noise considerably if a band filter is applied that allows the receiving signal to pass through its specific band only. It is important, however, to further reduce the grain noise for enhancing further the detectability of the Lamb wave inspection system so that more minute defects can be detected.

In this connection, the following can be considered as a means of improving detectability:

(1) To increase the number of frequencies of the generated ultrasonic wave.
(2) To use a plurality of Lamb wave modes together for defect detection.
(3) To improve detectability by signal processing.

In this research, emphasis was placed on the application of SSP, split spectrum processing, conventionally reported effective as a

---

[*1] Environment & Process Technology Center
[*2] Nittetsu Elex Co., Ltd.
[*3] Yawata Works

means for removing grain noise, for the improvement of detectability by signal processing. Several concrete techniques of SSP have so far been proposed, including Minimization algorithm, hereinafter abbreviated to Min, [1, 2]; Polarity thresholding algorithm, hereinafter abbreviated to PT,[3-5]; the method with the foregoing two combined together, hereinafter abbreviated to Min + PT,[6]; and Geometric mean filtering (GM)[7]. Theoretical analysis and experimental verification have been reported on the effectiveness of ultrasonic waveforms.

Since no exemplary report is available on the application of SSP to the Lamb wave inspection system, a study has been made of great technical problems concerning whether SSP can be made effective for narrow-band Lamb waves and how real time processing of SSP can be realized. As a result, a system by which SSP can be processed real time has been successfully developed after confirming the improvement of the detectability of the defects of sample steel strips with natural defects and completely synchronizing with the online Lamb wave inspection system detecting defects repeatedly at a frequency of 500 Hz by the appropriate selection of SSP parameters. This summary will be reported below.

2. Application of SSP to Lamb waves

In the technique of SSP, as **Fig. 1** shows, the data of n waveforms, $r_j(t)$ ($j = 1, \cdots, n$), is obtained after the passing band has first allowed the ultrasonic wave receiving signal, $r(t)$, to pass through the n adjoining filters, and the final output, $y(\tau)$ is set against $r_j(\tau)$ by nonlinear processing at time(τ). There are three kinds of nonlinear processing represented by equations (1) to (3). In the case of the echo from the defect, it is highly likely that the data of n waveforms, $r_j(\tau)$, has the same plus and minus waveforms in the same phase, whereas it is very likely that in the noise signal, such as grain noise, plus and minus waveforms are present mixed together due to the irregular phase. The principle of SSP may therefore be considered a method of removing noise by taking advantage of the above difference. Still more, the study of optimization is necessary, because as Fig. 1 shows, the parameters of SSP include the number of filters, n, each filter band, b, the central frequency of the first filter, f_1, and the distance between the central frequencies, D_f.

(1) Min

$$y(\tau) = r_k(\tau) \qquad \cdots\cdots (1)$$

here, $|r_k(\tau)| = \min\{|r_j(\tau)|, j = l, ..., n\}$

(2) PT

In case all of $r_j(\tau)$ are either plus or minus, $y(\tau) = r(\tau) \quad \cdots\cdots (2)$

In other case, $y(\tau) = 0$

(3) Min + PT

In case all of $r_j(\tau)$ are either plus or minus, $y(\tau) = r_k(\tau) \quad \cdots\cdots (3)$

In other case, $y(\tau) = 0$

here, $|r_k(\tau)| = \min\{|r_j(\tau)|, j = l, ..., n\}$

As regards the processing in the time zone of SSP, the band-pass filter is represented by equation (4) indicating the impulse response of the n adjoining filters[8]. Here, the band-pass filters of Gaucian type are assumed, and b indicates the filter band, f_j, the central frequency of the j-th filter, and $f_j = f_1 + (j - 1) D_f$

$$h_j(t) = 2\sqrt{\pi b}\, e^{-(\pi b t)^2} \cos(2\pi f_j t) \qquad \cdots\cdots (4)$$

Actually, the digital signal is processed in sampling time T_s. Therefore, after passing through the filters all the signals are represented by the following equation, and the final output is obtained after nonlinear processing as shown in equations (1) to (3)[8]. It is to be noted that this equation, representing $h_j(t)$ of equation (4) by the limited time zone, samples its function in sampling time T_s so that it comes to the L-th from the –L-th. Here, k is an integer.

$$r_j(kT_s) = \sum_{i=-L}^{L} 2\sqrt{\pi b}\, T_s e^{-(\pi b i T_s)^2} \cos(2\pi f_j i T_s)\, r((k-i)T_s) \qquad \cdots\cdots (5)$$

The Lamb wave inspection system used for the online evaluation test detects defects using toneburst waves with a frequency of about 2.25 MHz. As **Fig. 2** shows, the existing Lamb wave inspection system is so designed that it enables to generate Lamb waves and repeated signals for defect detection (PRF signals) from it. It converted a waveform to 8-bit AD to record digital data in the personal computer (PC), and carried out SSP later. Again, sampling at 20 MHz was carried out to respond to the use of the toneburst waves with a frequency of about 2.25 MHz.

Since it is necessary to optimize various parameters in the application of SSP, steel strips were rendered artificially defective with holes pierced, and raw signals were recorded. Then, the extent to which SN improved by SSP was investigated by varying the parameters. As a result, it was found optimal to carry out the Min + PT method with the number of filters n = 10 and each filter tap number = 500. It was therefore decided to apply those parameters in the later processing. It was also decided to cover Lamb wave frequency range from 2.1 to 2.4 MHz with 10 filters, and each filter band b and the distance between the central frequencies, D_f, were set in $b = 4 D_f$ by referring to the past report[8].

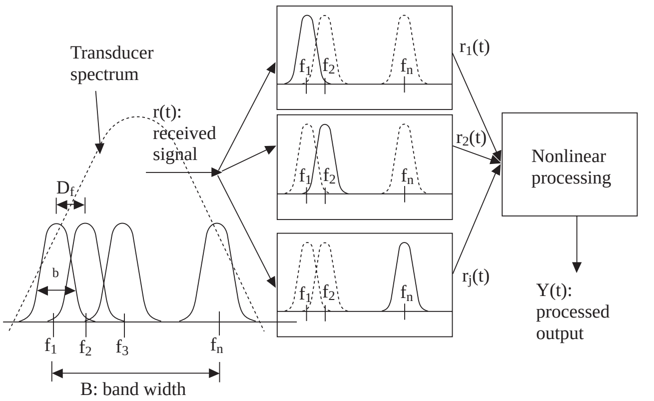


Fig. 1 Outline of nonlinear signal processing SSP

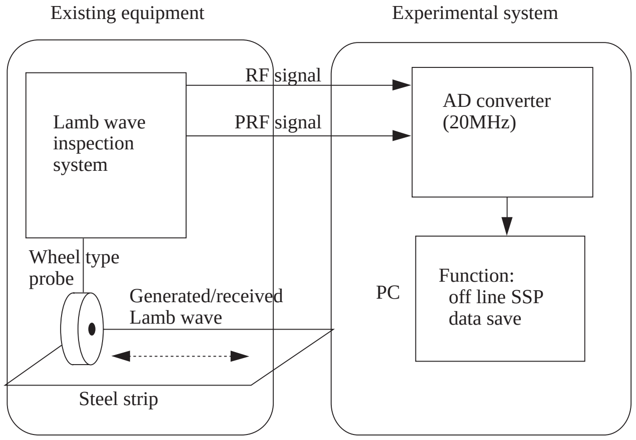
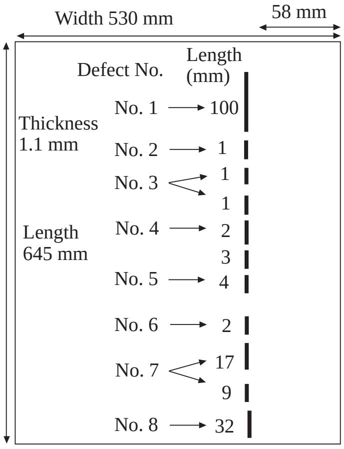


Fig. 2 Block diagram of offline evaluation test system

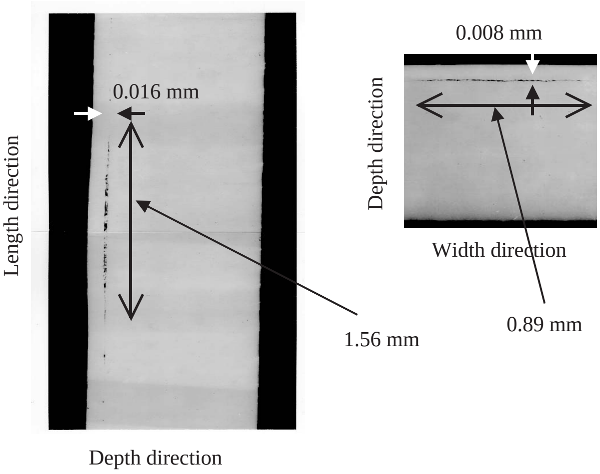
3. Tests for evaluating the application of SSP to steel strips with natural defects

Since natural defects are not uniform, and varied in the position of their presence even in the width direction, tests were carried out to confirm whether SSP is effective for steel strips with natural defects. **Fig. 3** shows the examples of steel strips with natural defects. They are samples with defects barely detected by visual inspection, because the steel strip surface is slightly swelled due to the foam produced inside. It is impossible to detect such a minute defect by the online Lamb wave inspection system now in use. Fig. 3(a) is a schematic diagram of the top surface of a steel strip, and a group of linear defects is formed due to the foam produced slenderly in the longitudinal direction. Fig. 3(b) shows the photos of cross-sectional observation of natural defect No. 2 shown in (a). The volume of the defects, when calculated, is in the order of about 0.001 mm^3.

Fig. 4 gives a comparison of waveforms before and after the application of SSP when raw signals were emitted. They are examples of defects Nos. 4 and 6 present at the upper part of the steel strip shown in Fig. 3. The examples of the waveforms clearly indicate that the noise signals before and after the defective parts and from the periphery of the edge parts can be reduced, and that each defective part can be detected clearly. To give the extent of improvement by SSP of SN more quantitatively, the SN values of the raw signals of each defective part and the SN values after SSP were calculated. **Fig. 5** shows the results. The SN values were calculated based on the definition that they are the values of the defective signal amplitude/



(a) Schematic diagram of the top side of strip



(b) Photo of cross-sectional observation of No. 2 defect

Fig. 3 Outline of steel strips with natural defects, used for evaluation tests

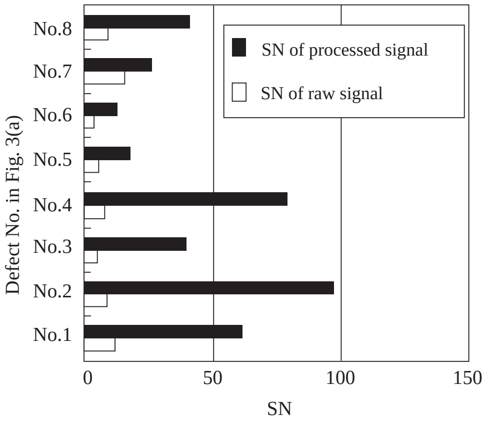


Fig.5 Comparison of the SN values of waveforms before and after application of SSP

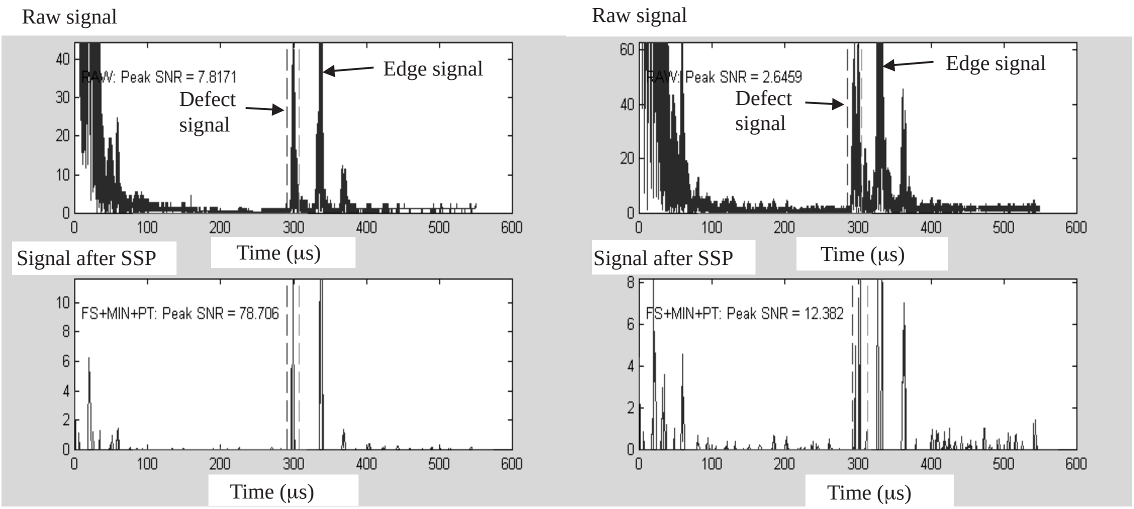


Fig. 4 Comparison of waveforms before and after application of SSP

maximum noise amplitude in a range except for each dead zone of the generated Lamb wave side and edge part for one waveform. Fig. 5 shows that SN was improved by SSP in every defective part.

4. Realization of real time SSP

Next, a study was made of a system that can be used online. As Fig. 1 and equation (5) clearly show, SSP is a combination of a linear filtering processing with a nonlinear one. This makes it difficult to carry out real time processing. No report has therefore been made on an online inspection system with SSP incorporated[9]. In this research, an attempt was made to carry out real time processing of SSP using software so that the parameters of SSP can be set up more flexibly.

Assuming the number of filter taps to be used for SSP filtering as m(= 2L + 1), it is necessary for the operation of each filtering processing in equation (5) to multiply m times and add (m – 1) times, a total of (2m – 1)-time operations. Accordingly, if the number of sampled data is N, the total number of operations, A, arrives at $A = n \times N \times (2m - 1)$. Next, assuming the width of a steel strip as L (m) and the phase velocity of Lamb wave mode to be used for defect detection as V (m/s), the time before the reflected echo reaches from the steel strip edge part, T (s), comes to $T = 2L/V$. Therefore, the number of data that requires sampling, N, comes to $N = 20 \times 10^6 \times 2L/V$ in case of sampling at 20 MHz. Then, the total number of operations, A, can be represented by the following equation:

$$A = 40 \times 10^6 \times n \times (2m - 1) \times L/V \quad \cdots\cdots (6)$$

For example, in case L = 1.5 (m), V 3000.0 (m/s), m = 500, and n = 10, A is nearly equal to 2.0×10^8. It therefore follows that in case the repetition rate for detection is 500 Hz, operation speed B = A × 500 99.9 (GOPS) is required. In this study, however, the nonlinear operation of SSP as in equation (3) is not included.

Then, for drastic reduction of such vast number of operation times, processing before SSP operation shown in **Fig. 6** was devised. As Fig. 6 shows, AD-converted data is allowed to pass through the band pass filter containing the toneburst wave signal, and to process in such a manner that only one data within continuous 10 digital data are remained to carry out the SSP operation in the condition of the reduced number of data, N, and the number of filter taps, m, to 1/10 respectively. According to the sampling theorem, the data reduced to 1/10 retain the original one contained in the toneburst wave signal band. In other words, if no areasing is available when M is assumed as an integer, frequency as f, sampling frequency as f_s, and signal spectrum as X(f), X(f) equals to $X(f + Mf_s)$ corresponding to the case in which M = 2, $f_s = 1$ MHz, and $0.0 \le f \le 0.5$ MHz. In this case, the number of operations, A, is as shown below, and can be reduced, for example, to 11% of the number of operations in case of n = 10 and m = 500.

$$A' = N \times (2m - 1) + n \times N \times (m/5 - 1)/10 \quad \cdots\cdots (7)$$

It is to be noted that the processing to reduce the number of data samplings to 1/10 is not included in the number of operations, because processing time in the computer can be negligible. For further enhancement of throughput, a high-speed PC with more than two of the latest CPUs mounted was used, and general-purpose filtering processing was carried out by using MMX (multi media extension) so that the parallel processing of SSP operation and image processing and speed increase could be achieved.

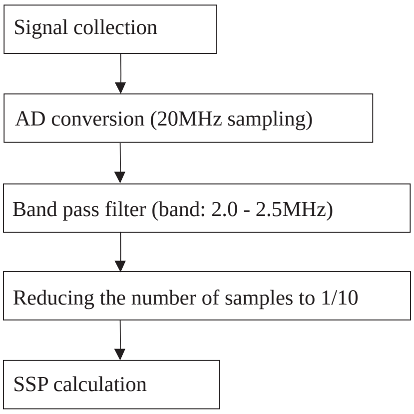


Fig. 6 Flowchart of data processing for realization of real time SSP

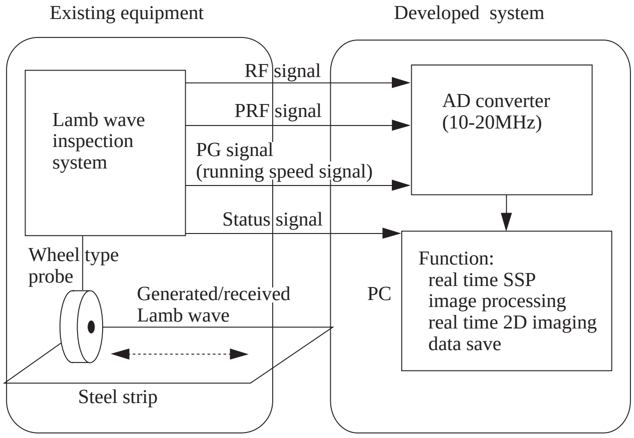


Fig. 7 Block diagram of the online wave inspection system provided with real time SSP functions

In this manner, drastic reduction of the number of operations along with parallel processing and speed increase could be achieved resulting in the realization of real time processing at a repetition rate of 500 MHz. **Fig. 7** gives a block diagram of the developed system. In this online system, the ultrasonic signal from the existing Lamb wave inspection system is converted to 12-bit AD at a maximum sampling frequency of 20 MHz, and the digital data is transmitted to the PC so that the results of real time SSP operation (16 bits are used for all operations inside the computer) and two-dimensional defect detection image can be displayed. Furthermore, this system is provided with a set up image for SSP parameters, enabling easily to set up or change parameters. What is more, any waveform (a raw waveform and a post-SSP waveform) judged defective can also be recorded real time, enabling to display again later[10, 11].

5. Conclusion

For enhancement of the detectability of the conventional Lamb wave inspection system used for the online detection of the internal defects of steel strips, a study was made of the application of SSP to Lamb waveforms and optimization of SSP using steel strips with natural defects prepared, and the improvement of defect detectability was confirmed. Furthermore, drastic reduction of the number of SSP operations and parallel processing were achieved for the realization of real time SSP operations. This resulted in developing a system as an online system by which SSP can be carried out at a repetition rate of 500 Hz, a rate sufficiently high for the system.

References

1) Newhouse, V. L., Bilgutay, N. M., Saniie, J., Furgason, E. S.: Ultrasonics. 20, 59(1982)
2) Karpur, P., Shankar, P. M., Rose, J. L., Newhouse, V. L.: Ultrasonics. 25, 204(1987)
3) Amir, I.: Ph.D. Thesis, Drexel University, Philadelphia, PA, June 1986
4) Benharit, U., Kaufman, J. L., Bilgutay, N. M., Saniie, J.: Proc. 1986 IEEE Ultrasonics Symp. 1986, p.1021
5) Bilgutay, N. M., Bencharit, U., Murthy, R., Saniie, J.: Ultrasonics. 28, 90(1990)
6) Rose, J. L., Karpur, P., Newhouse,V. L.: Mater. Eval. 46, 114(1988)
7) Xin, J., Donohue, K. D., Bilgutay, N. M., Li, X.: Mater. Eval. 49, 987(1991)
8) Aussel, J. -D.: Ultrasonics. 28, 229(1990)
9) Nakamura, M., Yokoyama, M. H., Yamano, M., Murayama, R.: Nondestructive Characterization of Material VIII, edited by R. E. Green Jr., Plenum Press, New York, 1998, p.235
10) Nagata, Y., Konnno, Y., Naito, S., Kubota, M., Kino, T., Sekiguchi, O., Hirowata, A.: CAMP-ISIJ. 12(5), 898(1999)
11) Naito, S., Nagata, Y., Konno, Y.: J. Signal Processing. 3(5), 325(1999)