Non-Destructive Inspection of Steel Billet Using Phase-Modulated and Multiplexed Gold Sequence

Gold 系列位相変調信号を同時に多重伝送する
角鋼片非破壊検査

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1. Introduction

Steel billets are primary casting product that serves as inputs for the production of steelworks. The steel billet may have defects inside [1]. Defects must be detected before shipping. Ultrasonic inspection is expected to detect defects in billet. The billet can be inspected non-destructively by ultrasound in production line. Currently, the pulse echo method is used in general. However, the defect, such as a slight or small defect, cannot be detected by the pulse echo method. Therefore, we have suggested the method of defect detection by ultrasonic computerized tomography (CT) method using time-of-flight (TOF) data [2]. In this method, the defect information is obtained from the increase of TOF caused by ultrasonic signal diffracting around the defect. However, it takes a lot of time to measure the TOFs because CT method requires the TOFs measured on all around of billet. In this study, to speed the TOF measurement, we suggest the measurement method by simultaneous transmission and reception using phase-modulated signal by multiplex Gold sequences and evaluate the measurement accuracy of TOF.

2. TOF measurement method

2.1 Measurement signal

In this study, the transmitted signal is the phase modulated signal by Gold sequence, which is made from two M-sequences. Gold sequence is one of the pseudo-noise sequences. The auto-correlation function of Gold sequence has a sharp peak. In addition, the cross-correlation function by two different sequences is small throughout. These characters are efficient for the TOF measurement by the cross-correlation method. The modulated signal is up-chirp signal although the sinusoidal signal is used generally [3]. The up-chirp signal has wider frequency band and sharper cross-correlation peaks than that of the sinusoidal signal. **Figure 1** shows the signal modulation process. The chirp signal, whose frequency is $1 - 3$ (MHz) and the number of waves is η, is assigned per a bit. This signal is phase-modulated by $(0, \pi)$ corresponding to the symbol of Gold sequence, $(0, 1)$.

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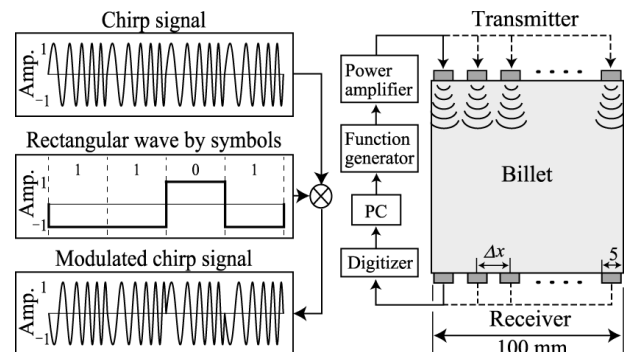{mizutani, wakatuki}@iit.tsukuba.ac.jp

Fig. 1 Modulating process.　Fig. 2 Measured plane.

2.2 Extraction of TOF

TOF is extracted by the cross-correlation method between the transmitted and received signals in general [4]. In this study, TOF is extracted by the periodic cross-correlation between the transmitted wave of $T = 1$ and the received wave of $T = 3$, where T is the period of the Gold sequence. The difference of TOF, $\Delta\tau$, which is used for reconstruction by ultrasonic CT method, is derived from difference between measured TOF and calculated TOF by ray theory. This method is named as Method I. However, in this study, $\Delta\tau$ is calculated by the periodic cross-correlation between a reference signal and the received signal. This method is named as Method II. The reference signal is measured by a pair of transducers at every measurement point using the transmitted signal of $T = 1$. By using the reference signal, it is possible to cancel the radiation characteristics between the transmitter and the receiver. The frequency characteristic of transducer is also canceled. The transducer has the frequency limiting. Therefore, in case that the transmitted signal is code-modulated signal, wave distortion by the frequency characteristic of the transducers is large because of the wide band signal. Hence, measurement errors much decrease using Method II.

3. TOF measurement by experiment

3.1 Condition and evaluation

We evaluated the measurement accuracy of $\Delta\tau$ by experiment. **Figure 2** shows the measured plane. The billet is made of duralumin, whose size is $100 \times 100 \times 100$ (mm^3). The measurement plane has no defects. The aperture of transducer is 5 mm.

The transmitters and receivers were arranged at equal interval, Δx. The transmitted wave was phase-modulated by 5th-order Gold sequence, and periodic cross-correlation function between the received wave and the transmitted wave or the reference wave was calculated. In this study, due to limitations of experimental equipment, we assume the received signal as the sum of the measurement signals from each transmitter to one receiver. $\Delta \tau$ was calculated by Method I and II. The accuracy of $\Delta \tau$ was evaluated by SINR (Signal to Interference and Noise Ratio), defined as

$$SINR = 10 \log_{10}(S/IN) \quad \text{(dB)}, \quad (1)$$

$$S = \int_{t-\Delta t}^{\tau+\Delta t} \Phi(t)^2 dt, \quad IN = \int_{t+\Delta t}^{\tau+T/2} \Phi(t)^2 dt.$$

where Δt was the time from the peak to the first zero crossing point after the peak in the autocorrelation function of the transmitted signal. In addition, the accuracy of $\Delta \tau$ was evaluated by the ratio of accurate measurement, R, which was the ratio of the measurement points satisfying $-0.1 \leq \Delta \tau \leq 0.1$ (μs) to all measurement points. Under this condition about $\Delta \tau$, detecting a defect whose diameter is 2 mm is possible.

3.2 Experiment result

We measured the transmitted, received, and reference signals by varying $\Delta x = 5, 10, 20, 25, 50$ (mm), and $\eta = 1, 3, 5, 7$ by Method I and II. The number of transmitters was 20, 10, 5, 4, 2, corresponding to $\Delta x = 5, 10, 20, 25, 50$ (mm). **Figure 3**(a) and (b) show one of the normalized cross-correlation functions at $\Delta x = 10$ mm, and $\eta = 5$ obtained by experiment. According to Fig. 3(b), it was found visually that the interference waves were suppressed by Method II. Figure 3(c) – (e) show relationship between R and $SINR$ varying η. The horizontal axis shows the scan pitch, Δx. Fig. 3(c) and (e) show the results by Method I and (d) and (f) show that by Method II. First, we compared R and $SINR$ in various η. When $\eta = 1$, R and $SINR$ were not large. The frequency band of the transmitted signal becomes wider as the bit time becomes shorter. Therefore, the transmitted signal is distorted by band limiting of the transducer, and results in the worse measurement accuracy. On the other hand, comparing $\eta = 5$ and 7, $SINR$ was almost equal in Fig. 3(e) and (f). R of $\eta = 5$ was larger than that of $\eta = 7$ in Fig. 3(d). Here, comparing Method I and Method II, R and $SINR$ by Method II were larger than those by Method I. This is because the effect of band limiting of transducer positional relation of transducers can be suppressed. In addition, according to the results at $\eta = 5$ and 7, it was considered that beyond $\eta = 5$, there was little change about the effect of suppression of band limiting. Under the condition that the measurement
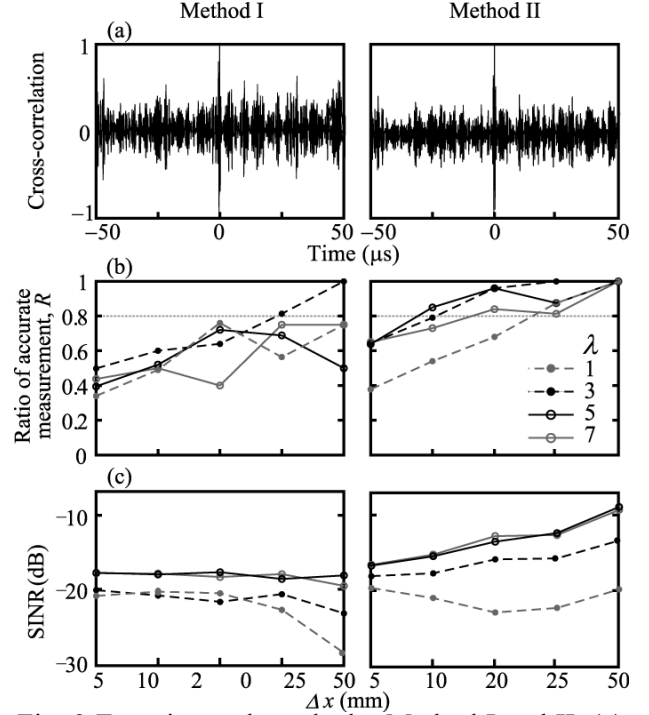

Fig. 3 Experimental results by Method I and II. (a): Cross-correlation function between received and transmitted signal, (b): Ratio of accurate measurement, (c): SINR.

accuracy is almost equal, the shorter signal is effective to measure due to low calculation cost and short measurement time. In case that the TOF data are reconstructed by ultrasonic CT, which was used in our previous paper [5], defect can be detected by TOF data including about 20 % of measurement error. According to Fig. 3 (d), in $\Delta x = 10$ mm, $R > 0.8$ was satisfied by only $\eta = 5$. As a result, simultaneous transmission and reception is possible in $\Delta x = 10$ mm and $\eta = 5$ by Method II.

4. Conclusions

To speed the measurement of TOFs, we suggested the simultaneous transmission and reception method and evaluated the measurement accuracy of TOF by experiment. Transmitted wave was phase-modulated by Gold sequence. When the reference wave was used to calculate the increase of TOF, the measurement accuracy improved. As a result, we found out that simultaneous transmission and reception is possible in $\Delta x = 10$ mm and $\eta = 5$.

References
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