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Application of Nondestructive Inspection Method to Shape-distorted Billet Using Simultaneous Measurement of Multiple Time-of-flight

縦波伝搬時間複数同時計測を用いる非破壊検査法の形状ひずみを持つ角鋼片への適用

Yoko Norose[‡], Koichi Mizutani, and Naoto Wakatsuki (Univ. Tsukuba)
野呂瀬　葉子[‡] (筑波大院・シス情工), 水谷　孝一, 若槻　尚斗 (筑波大・シス情)

1. Introduction

We have proposed a nondestructive inspection method for a steel billet using ultrasonic computerized tomography (CT) with time-of-flight (TOF) of longitudinal wave[1]. In this method, existence of a defect is can be estimated from increment of TOFs caused by ultrasonic wave diffraction and scattering around a defect[2,3]. In case of a shape-distorted billet, it is difficult to measure TOFs accurately because TOF measurement error is superposed by the shape distortion[4]. In order to reduce TOF measurement error, we have proposed a TOF measurement method using a reference plane[5]. A billet is devided into cross-sections and the inspection is performed on each plane. The reference plane means the preceding plane of the measurement plane. In this method, TOF is calculated from the received signals on the measurement plane and the reference plane under the assumption that the change of the cross-sectional shape is smooth in longitudinal direction. It is possible to compensate the transfer characteristics between the transmitter and the receiver and the measurement error by the shape distiortion. However, in simultaneous measurement of TOFs for speeding up, this method is not appropriate because the received signals on the reference plane are measured by sequential transmissions[6]. Therefore, in this paper, we propose a TOF measurement method, which can be applied to the shape-distorted billet in simultaneous measurement, and verify the performance of this method by the numerical simulation.

2. TOF measurement method

Figure 1 shows the outline of the TOF measurement methods. Figures 1(a) and (b) show the previous method (Method I) and the proposed method (Method II), respectively. In Method I, the defect information is obtained by the TOF difference $\Delta\tau$. $\Delta\tau$ is obtained by calculating the cross-correlation function between the reference signal $r(t)$ and the measurement signal $m(t)$, those are measured on the reference plane and the measurement plane, respectively. In this paper, the reference plane is assumed to be a defect-free and the measurement plane is assumed to have some defects. It is unable to speed up by simultaneous multiple transmissions by Method I, because Method I needs the reference signal, which is the received signal measured by sequential transmission on the reference plane. Therefore, we propose a TOF measurement method which is possible to be used for a shape-distorted billet in simultaneous transmissions. In Method II, at first, we obtain standard reference signals. The standard reference signal $r_0(t)$ means the received signal measured by the sequential transmission on the standard reference plane. In this study, the standard reference plane is assumed to be a square and defect-free plane. TOF difference $\Delta\tau$ is obtained by the difference between $\Delta\tau_z$ and $\Delta\tau_{z\text{-}\Delta z}$. $\Delta\tau_z$ and $\Delta\tau_{z\text{-}\Delta z}$ are obtained by calculating the cross-correlations between the measurement signal $m_z(t)$ and the standard reference signal $r_0(t)$, and the reference signal $r(t)$ and $r_0(t)$, respectively. Consequently, in the proposed method, sequential measurement is required only once on the standard reference plane, and following measurements on measurement planes can be performed simultaneously. In Method II, it is possible to reduce both the effect of TOF measurement error by shape distortion and the effect of the transfer characteristics of transducers.

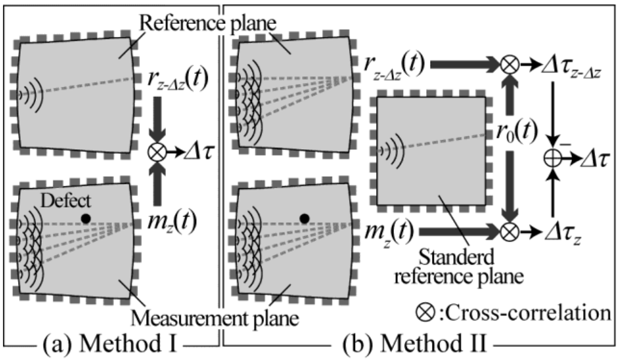

Fig. 1 Outline of TOF measurement method: (a) Method I (previous method), and (b) Method II (proposed method).

3. TOF measurement accuracy

At first, we investigate the TOF measurement accuracy by Method I and II by the numerical simulation. The test piece is assumed to be made of steel, whose sound velocity is 5,950 m/s. The size of its cross-section is 100×100 (mm^2). The shape

norose@aclab.esys.tsukuba.ac.jp
mizutani@iit.tsukuba.ac.jp
wakatuki@iit.tsukuba.ac.jp

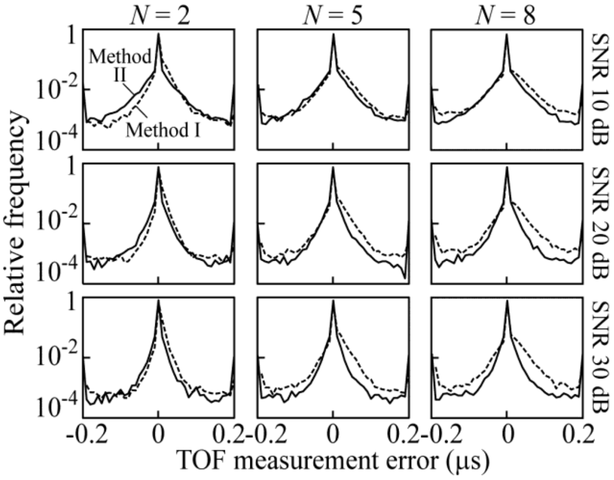

Fig. 2 Relative frequency distribution of measurement error in simultaneous measurement of TOF.

distortion is designed by sine curve, whose amplitude is less than 5 mm. In this section, to investigate the TOF measurement accuracy, both the reference and measurement plane are assumed to be defect-free. The transducers are arranged on the billet surface in 2 mm step. Transmitted signal is half-sine pulse, which is phase-modulated by Gold sequence of 5th order. Considering the small signal-to-noise ratio (SNR) environment, white Gaussian noise is added to the received signals. The number of the simultaneous transmissions N is varied in 2, 5, and 8. The relative frequency of TOF measurement error is calculated by the simulation.

The result is shown in Fig. 2. These figures show relative frequency distribution of TOF measurement error, whose vertical axis is log scaled. In Fig. 2, the variance of TOF measurement error increases as SNR becomes small in both Method I and II. In Method I, the variance increases with increase of N. On the other hand, in Method II, the variance does not change with N. This result supposes that Method II is efficient for the simultaneous measurement of TOF.

4. Defect visualization by ultrasonic CT

Next, we verify validity of Method II by visualizing a defect using ultrasonic CT. Setup image in Fig. 3 shows the arrangement of the defect in the measurement plane. The other simulation conditions are the same as §3. Figure 3 shows the CT images obtained by the simulation. In Method I, when N = 8, it is difficult to distinguish the defect from artifacts in the CT images. On the other hand, in Method II, the defect is visualized clearly regardless of SNR. This result supposes that in Method II, the TOF measurement error decreases by SNR increment which is caused by deriving $\Delta\tau$ from difference between $\Delta\tau_z$ and $\Delta\tau_{z-\Delta z}$ obtained by the pulse compression of the received waves. As a result, Method II is useful in the simultaneous measurement of TOF for shape-distorted billet.

5. Conclusions

In this paper, we proposed the TOF measurement method in simultaneous measurement for the shape-distorted billet, and verified the validity of the proposed method by the numerical simulation. From the simulation results, it was recognized that it was possible to measure TOF simultaneously and to visualize a defect by the proposed method. Moreover, compared with the previous method, the proposed method was robust over noise and interferences. Therefore, it was suggested that the number of the simultaneous transmissions increased by the proposed method.

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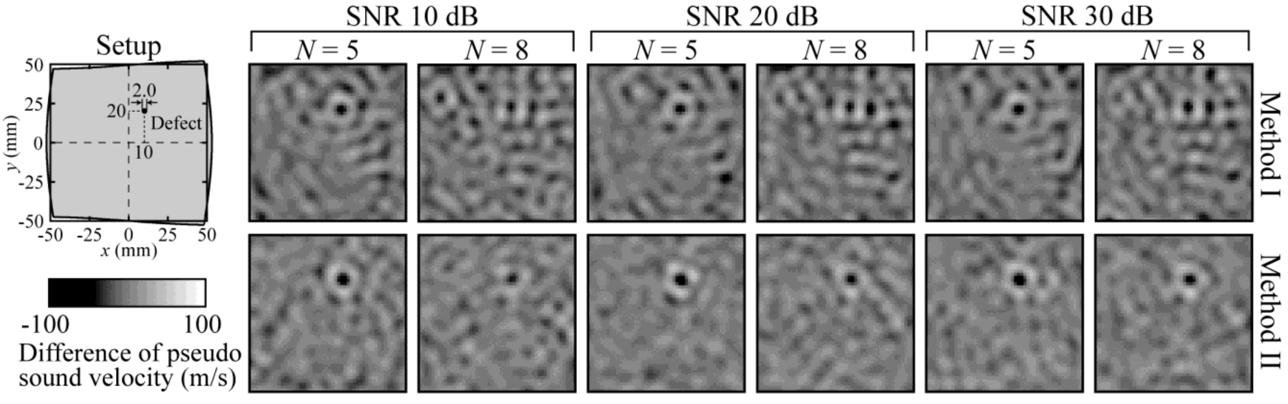

Fig. 3 Defect visualization image by ultrasonic CT in simultaneous measurement.