Study on Accuracy Improvement in Ultrasonic Thermometry Based on Pulse-Echo Method

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Introduction. It is known that ultrasonic thermometry is a useful method to make noninvasive and nondestructive measurements of internal temperatures of heated materials. When a thin layer less than one wavelength of ultrasonic waves is in contact with the back surface of a material to be estimated, multiple reflections within the layer occur and result in the deformation of the ultrasonic waveform reflected at the back surface. Such deformation easily leads to some error in the estimated transit time of the ultrasonic wave, and consequently deteriorates the accuracy in measuring temperatures by the ultrasonic thermometry. In this work, the influence of such waveform distortion on temperature measurements is investigated theoretically. The validity of the investigation has then been demonstrated experimentally.

Method. The ultrasonic thermometry consisting of ultrasonic pulse-echo measurements and a one-dimensional heat conduction analysis using finite difference calculations¹ is employed in this work. The heated-surface temperature at a time step \( n+1 \) in this method, \( T_{n+1}^{s+1} \), is given by

\[
T_{n+1}^{s+1} = -\frac{1}{A} \left( \frac{t}{h} - \frac{1}{v_n^s} + 2 \sum_{i=2}^{N} \frac{1}{v_i^s} \right) + \frac{B}{A} \tag{1}
\]

where \( t \) is the transit time of ultrasonic wave, \( h \) is the grid interval, \( N \) is the number of the grid, \( v_i^s \) is the ultrasonic velocity at each grid position, \( i \) and \( n \) are indices corresponding to spatial coordinate and consecutive time in the finite difference calculation. \( A \) and \( B \) are the coefficients determined from the temperature dependence of the ultrasonic velocity. When the ultrasonic transit time has an deviation \( \Delta t \), the error of the surface temperature is given by

\[
\Delta T_{n+1}^{s+1} = \frac{\partial T_{n+1}^{s+1}}{\partial t} \Delta t = \frac{\Delta t}{Ah} \left( \frac{1}{v_n^s} + 2 \sum_{i=2}^{N} \frac{1}{v_i^s} \right) \tag{2}
\]

Numerical estimation. When the thin layer is deposited on the back surface of a thick plate, the reflected waveform from the back surface can theoretically be predicted. It is noted here that the temperature inside the plate is assumed to be uniform. In the prediction, a convolution of the complex reflectance from the back surface with a thin layer deposition and the spectrum of reflectance without deposition is performed and the inverse Fourier transform \(^{(2)}\) of the convolution is made. The transit time of ultrasonic wave is determined from the reflection waveforms by either the cross-correlation method (CC) or the zero-crossing method (ZC). Using the transit time, the error of the heated-surface temperature \( \Delta T_{n+1}^{s+1} \) was then estimated form Eq. (2). Thus, the influence of the layer thickness on the ultrasonic thermometry is investigated.

Result. Figure 1 shows the variations in the errors of the surface temperature with the layer thickness. Since the distortion of the waveform strongly depends on the layer thickness, the estimated surface temperature also fluctuates with the layer thickness. It is seen in Fig. 1 that the deviation range of the estimated temperature by the CC is larger than that by the ZC. Thus, it was found that the surface temperature error can be reduced by using the ZC rather than using CC. Since the ultrasonic thermometry utilizes difference calculations for estimating temperature distribution, the surface temperature plays an important role in estimating internal temperature distribution of the plate. This issue is discussed with experimental results.

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References.