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Improved Practicality of Ultrasonic Thermometry Utilizing Longitudinal and Transverse Waves

縦波と横波を活用した超音波サーモメトリの実用性向上

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1. Introduction

Measuring temperature is one of the fundamental issues in various fields of science, engineering and industries. In particular, measuring surface or internal temperature for heated materials and structures are frequently required and even indispensable. Therefore, there are increasing demands for realizing an effective method for making noninvasive and real time measurements of those temperatures. To meet such requirements, so-called "ultrasonic thermometry" which is a method for measuring temperature by ultrasound has been studied extensively. Recently the effective ultrasonic method for measuring internal and surface temperature profiles has been proposed and its feasibility has also been demonstrated [1-5]. Because of its distinctive feature of the method, it is highly expected to apply such method to various materials, structures and processing. In those methods, because the temperature dependence of the ultrasonic velocity of the measurement object is indispensable for the temperature estimation, such temperature dependence should be prepared prior to the estimation of the object. It should be noted that such temperature dependence has to be prepared for each measurement object. Obtaining such temperature dependence is usually not easy and sometimes even impossible for some applications. This is a problem that has hindered the versatility of the method.

To overcome the problem, in this work, a method that compensates for the influence of thermal expansion of the measurement object has been proposed. In the method, both longitudinal and transverse ultrasonic waves are employed for measuring the transit time of each wave propagating through the measurement object, and those transit times are then used for determining internal temperature distribution of the object. The validity of the proposed method is verified with a numerical model prepared for a one-dimensional heating object.

2. Method

The principle of the ultrasonic thermometry is based on temperature dependence of the velocity of the ultrasonic wave that propagates through a material. Assuming that there occurs one-dimensional temperature distribution in a material by a single side heating and the length of the medium varies from L to $L + \Delta L$, the transit time of ultrasonic wave propagating in the direction of the temperature distribution can be given by

$$t_L = 2\int_0^{L+\Delta L} \frac{1}{v_L\left(T\left(x\right)\right)}dx \tag{1}$$

$$t_S = 2\int_0^{L+\Delta L} \frac{1}{v_S\left(T\left(x\right)\right)}dx \tag{2}$$

where t_L and t_S are transit times for longitudinal and transverse waves, respectively, $v_L(T(x))$ and $v_S(T(x))$ are the ultrasonic velocities for longitudinal and transverse waves, respectively, that are a function of temperature distribution $T(x)$ in the direction x. The temperature dependence of ultrasonic velocity $v(T)$ depends on the material and may have an approximate linear relation.[1-3]

$$1/v_L\left(T\right) = A_L T + B_L \tag{3}$$

$$1/v_S\left(T\right) = A_S T + B_S \tag{4}$$

where, A_L , B_L , A_S and B_S are material constants.

A one-dimensional finite difference model composed of a large number of small elements and grids is used for analyzing the temperature distribution in x direction. Using a concept of trapezoidal integration, the transit time t_L and t_S given in Eqs. (1) and (2) can approximately be calculated from[1-3]

$$t_L = h\left(\frac{1}{v_{L,1}^{\,n}} + \frac{1}{v_{L,N}^{\,n}}\right) + 2h\sum_{i=2}^{N-1}\frac{1}{v_{L,i}^{\,n}} \tag{5}$$

$$t_S = h\left(\frac{1}{v_{S,1}^{\,n}} + \frac{1}{v_{S,N}^{\,n}}\right) + 2h\sum_{i=2}^{N-1}\frac{1}{v_{S,i}^{\,n}} \tag{6}$$

where $h = \left(L + \Delta L\right)/N$ is the grid interval, N is the number of the grid, v_i^n is the ultrasonic velocity at each grid position, i and n are indices corresponding to spatial coordinate and consecutive time, respectively. Now, we consider a plate having uniform temperature T_i^n at time n. if the single side of plate is heated, after a very short elapsed time n+1, temperatures at each point can be given by[1-2]

$$T_i^{n+1} = T_i^n + r\left(T_{i+1}^n + T_{i-1}^n - 2T_i^n\right) \qquad (i = 2, \cdots, N-1) \tag{7}$$

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$$r = \frac{\alpha\tau}{h^2} \quad (8)$$

where α is the thermal diffusivity, τ is the time step. Using Eqs. (5) and (6) and the temperature dependences (3) and (4), the temperature of the heated surface at time step n+1, T_1^{n+1}, can be given by

$$T_1^{n+1} = \frac{C_S t_L - C_L t_S}{A_L t_S - A_S t_L} \quad (9)$$

where

$$C_S = \left(\frac{1}{v_{S,N}^{n+1}} + 2\sum_{i=2}^{N-1} \frac{1}{v_{S,i}^{n+1}} + B_S \right) \quad (10)$$

$$C_L = \left(\frac{1}{v_{S,N}^{n+1}} + 2\sum_{i=2}^{N-1} \frac{1}{v_{S,i}^{n+1}} + B_S \right) \quad (11)$$

Because Eqs. (9), (10) and (11) are independent from the grid interval h, it is possible to calculate the heating surface temperature without being affected by the material elongation due to thermal expansion during heating of the material.

3. Validation with Numerical Experiment

In order to examine the validity of the proposed method, a numerical model for one-dimensional unsteady heat conduction by single side heating is prepared. The transient variation of the internal temperature distribution of the model is sequentially calculated and used as true values to be obtained experimentally. The specimen used in the numerical experiment is a steel plate of 30 mm thickness. In the experiment, the temperature of the steel is 25 °C before heating, and the single surface of the steel is heated uniformly for 3 s at 500 °C and then cooled for 2 s at 50 °C. The temperature at non-heating surface is being kept to be 25 °C. The thermal diffusivity α of the steel is 11.8×10^{-6} m^2/s. The variation in the temperature distribution in the steel is calculated under the boundary condition by the finite difference analysis with the time step τ = 0.04 s and the grid interval h = 1 mm to obtain the accurate value of the temperature distribution.

Figure 1 shows the variations in the transit times for longitudinal and transverse waves obtained from Eqs. (5) and (6), respectively, where the coefficients of Eqs. (3) and (4) are $A_L = 1.47\times10^{-8}$, $B_L = 1.65\times10^{-4}$, $A_S = 4.29\times10^{-8}$, $B_S = 3.03\times10^{-4}$. The steel length is calculated using the thermal expansion coefficient $k = 12.1\times10^{-6}$ K^{-1}. It can be seen in **Fig. 1** that the transit times increase drastically corresponding to the temperature rise in the steel and then decrease rapidly due to the temperature drop.

Using the transit times, the temperature profiles and their variations are determined by the proposed method from Eq. (9). **Figure 2** shows the variations in the temperature profiles with the elapsed time. We can see that the profiles determined by the proposed method agree well with the true values, whereas the results by the former method have a certain discrepancy with the true values. Thus, it has been demonstrated that the proposed method does work properly.

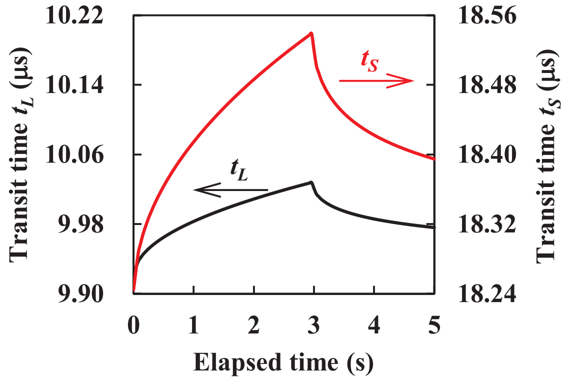

Fig.1 Variations in the transit times of longitudinal and transverse waves during heating and cooling.

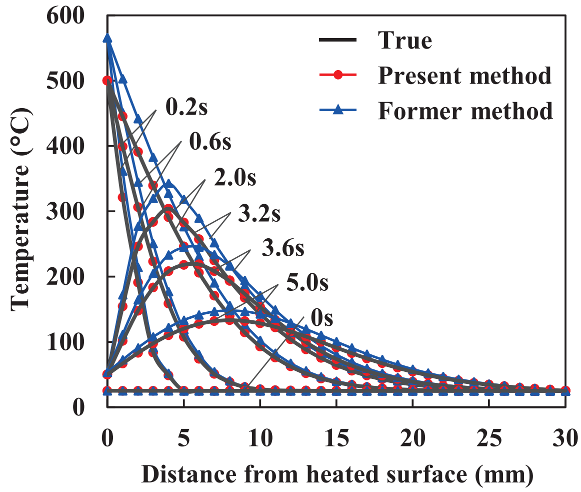

Fig. 2 Variations in temperature profiles of the steel during heating and cooling.

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