Application of Laser Ultrasound to Noncontact Temperature Profiling of a Heated Hollow Cylinder

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Abstract. A new ultrasonic method to monitor the temperature distributions of a thick-walled hollow cylinder whose inner surface is heated is presented. This method basically consists of laser ultrasonic measurements and a heat conduction analysis of the heated hollow cylinder. Both longitudinal wave (LW) and surface acoustic wave (SAW) are used for estimating the temperature distribution of the cylinder. To demonstrate the validity of the proposed method, a numerical simulation and an experiment are carried out. In the numerical simulation, a steel hollow cylinder (the inner and outer diameters are 20 mm and 100 mm, respectively) is uniformly heated by a constant heat flux at the inner surface. It has been verified in the simulation that temperature distributions estimated by the proposed method completely agreed with the theoretical results. In the experiment, an aluminum hollow cylinder (the inner and outer diameters are 20 mm and 50 mm, respectively) is heated by pouring molten metal at 300 ^{o}C into the hollow cavity of the cylinder. A laser ultrasonic system is used for measuring both LW and SAW of the heated cylinder. It has also been demonstrated that the proposed method can measure the change in the temperature distribution during heating.

1. Introduction

There is an increasing demand for temperature measurements of heated materials in the fields of engineering and industry. In particular, it is urgently required to monitor and control internal temperatures of hollow pipes or vessels filled with high temperature fluids or gases because the temperature state of such pipes is directly related to serious damage of pipes due to chemical reactions, corrosion, erosion, thermal stress and thermal fatigue. It is, therefore, imperative to develop an accurate in-situ monitoring technique of internal temperature distributions of heated pipes or vessels.

Ultrasound, owing to its high sensitivity to temperature, is expected to be a promising candidate for measuring the temperature of materials. Because of the advantages of ultrasonic measurements such as non-invasiveness and faster response, some works on the application of ultrasound to temperature estimation have been carried out extensively [1]-[6]. In our previous works [7]-[9], an effective methods consisting of an ultrasonic time-of-flight measurement and a heat conduction equation were developed for measuring temperature distributions of heated materials. The advantage of this method is that there is no need for the thermal boundary conditions at the heating surface where the thermal state is often unstable and difficult to know properly.

In this work, based on our previous methods [7]-[9], a method with a laser ultrasonic technique for monitoring the temperature distributions of a thick-walled hollow cylinder has been developed. To demonstrate the feasibility of this method, numerical and experimental demonstrations are carried out.

2. Determining temperature distribution of a hollow cylinder

The principle of temperature determination by ultrasound is based on the temperature dependence of ultrasonic wave velocity. Assuming that a hollow cylinder is uniformly heated at the inner or outer surface and has a one-dimensional temperature distribution in the radial direction as shown in figure 1, transit times for a longitudinal wave (LW) propagating along the radial direction and a surface acoustic wave (SAW) propagating along the outer surface of the cylinder are given by

$$t_{LW} = \int_0^{L_{LW}} \frac{1}{v_{LW}(T(x))} dx \qquad (1)$$

$$t_{SAW} = \frac{L_{SAW}}{v_{SAW}(T)} \qquad (2)$$

where L is the propagation distance of the ultrasonic wave and v is the ultrasonic velocity which is a function of temperature T. It should be noted that the LW propagates along the radial direction and the SAW propagates along the outer surface. The temperature at the outer surface is simply determined from SAW using equation (2). The internal temperature distribution in the radial direction is then determined by solving a one-dimensional heat conduction equation in a cylindrical coordinate system [10]. To determine the temperature at the inner surface from equations (1) and (2), an ultrasonic time-of-flight measurement and a finite difference calculation to solve the heat conduction equation in the cylindrical coordinate system are effectively combined [7]-[9]. The inner surface temperature is then determined from the transit time of the LW and both surface and internal temperatures obtained precedently. The advantage of this method is that there is no need to know the thermal boundary conditions at not only outer surface but also inner surface at where the boundary condition is usually unknown. It is also noted that the present method can be applied to the temperature estimation of a material having an unsteady temperature distribution.

3. Numerical demonstration

To verify the validity of the proposed method, a numerical simulation for the ultrasonic temperature estimation is carried out. A steel hollow cylinder with an axisymmetric temperature distribution as shown in figure 1 is used as the simulation model. The cylinder with inner and outer diameters of 20 mm and 100 mm, respectively, is heated by a constant heat flux (500 kW/m^2) at the inner surface. At first, the temperature distribution of the cylinder and its variation during heating are theoretically obtained by solving the heat conduction equation [10]. From these results, the transit times of ultrasonic waves for LW and SAW are determined from the equation (1) and (2). Using the transit times, the temperature distributions are then determined from the procedure mentioned above (the proposed method). Both temperature distributions estimated by the proposed method and estimated theoretically with the heat conduction equation are compared with each other. In the numerical demonstrations, the thermal diffusivity coefficient α = 7.53 mm^2/s, time interval for the finite

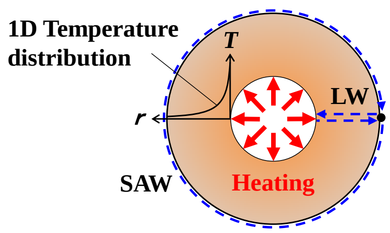

Figure 1. Schematic of an axisymmetric temperature distribution of an internally heated hollow cylinder and the LW and SAW propagations.

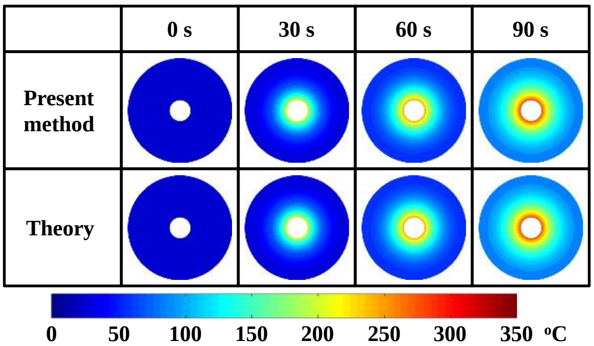

Figure 2. Comparison between the temperature distributions of the hollow cylinder estimated by the ultrasonic method and theoretical calculation.

difference calculation τ = 0.01 s, spatial interval for the finite difference calculation h = 1.0 mm, temperature dependence of the LW velocity v_{LW}=-0.763T+5736.2 m/s, and temperature dependence of the SAW velocity v_{SAW}=-0.538T+2895.9 m/s are used.

Figure 2 shows the estimated temperature distributions and their variations with the elapsed time after the heating starts. It can be seen that the temperature distribution in the cylinder changes gradually with the elapsed time. It is noted that the ultrasonically estimated results by the proposed method (upper) agree with the theoretically estimated results by the heat conduction equation (lower) completely. Thus, it is verified that the proposed ultrasonic method does work properly.

4. Experimental demonstration

Based on the numerical demonstration, the feasibility of the proposed method is demonstrated experimentally. Figure 3 shows the schematic of the experimental setup and the cross section of the cylinder used in the experiment. An aluminum hollow cylinder with inner and outer diameters of 20 mm and 50 mm, respectively, is used as the specimen and is uniformly heated by pouring molten metal at 300 °C into the hollow cavity of the cylinder. It should be noted that temperature distributions cannot be determined by numerical analyses because of lack of thermal boundary conditions. A laser ultrasonic system consisting of a pulsed laser generator (Nd:YAG, wavelength 1064 nm, energy 180 mJ, pulse width 3 ns) and a laser interferometer (Nd:YAG, wavelength 532 nm, power 200 mW) is used for measuring both LW and SAW. The two waves are continuously acquired every 0.033 s with a PC based acquisition system. The sampling rate of ultrasonic signals is 100 MHz. The transit time of each wave and its variation during heating is calculated by the cross correlation method. Using the transit times and their variations with the elapsed time, the temperatures at inner and outer surfaces and the temperature distributions of the cylinder are estimated. To compare with the ultrasonically estimated results, thermocouples are inserted into the cylinder at 5 and 10 mm from the inner surface

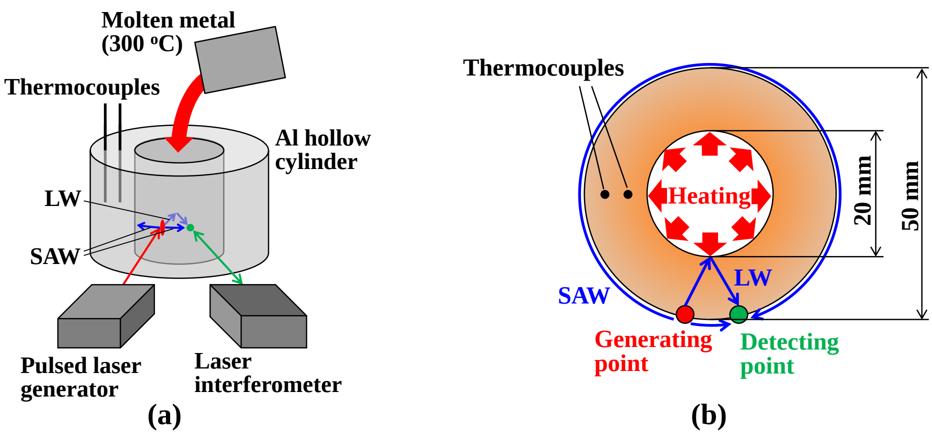

Figure 3. (a) Schematic of the experimental setup, (b) the cross section of the cylinder.

and used for internal temperature measurements. In the ultrasonic estimation, the thermal diffusivity coefficient α = 49.2 mm^2/s, temperature dependence of the LW velocity v_{LW}=-0.9797T+6428.9 m/s, and temperature dependence of the SAW velocity v_{SAW}=-0.8465T+2984.2 m/s are used.

Figure 4 shows variations in the temperature distributions of the cylinder with the elapsed time after heating starts, where the ultrasonically estimated results (line) are compared with those measured using the thermocouples. It can be seen that temperature distributions are gradually changed with the elapsed time. Although the ultrasonic results almost agree with those measured using the thermocouples, there are certain discrepancies between them in the early stage of heating such as within a few seconds after heating starts. This is likely because of relatively slow time response of the conventional thermocouples.

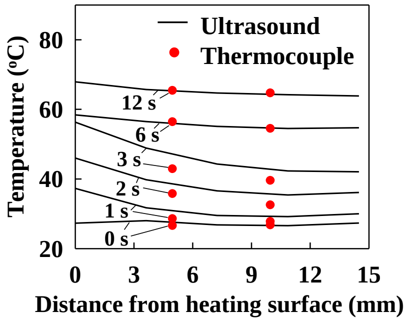

Figure 4. Variations in temperature distributions of the hollow cylinder with elapsed time, determined by the ultrasonic method (line) and measured using thermocouples (circle).

5. Conclusion

A noncontact ultrasonic method with a laser ultrasonic technique for measuring internal temperature distributions of a thick-walled hollow cylinder whose inner surface is heated, is presented. The validity of the proposed method is verified through a numerical simulation and its practical feasibility is also demonstrated experimentally. Although further study is necessary to improve the accuracy, practicability and robustness in the method, it is highly expected that the ultrasonic method could be a useful means for on-line temperature monitoring of hollow pipes or vessels filled with high temperature fluids or gases.

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