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Quantitative Evaluation of Transient Heat Flux through Solid Surface by Ultrasonic Thermometry
超音波サーモメトリを用いた固体表面から流入する熱流束の定量的評価

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1. Introduction

Heat flux is the rate of heat energy transfer through a given surface, and a fundamental and important quantity closely related to various thermal phenomena in sceince and engineering. Such thermal parameter is often indispensable for understanding physical phenomena related to the thermal conduction and thermal resistance of the heated materials. Quantitative information on heat flux is also required to make accurate theoretical or computational analyses of the heated materials. Therefore, it is required to conduct precise measurements of heat fluxes through a material surface during its heating or cooling process. Althogh conventional sensors are available for measuring heat flux, they have some problems; 1) difficulty in installing the sensor, 2) influence by the thermal mass of the sensor, and 3) relativerly slow time response in measuments. Therefore, noninvasive and *in-situ* measurements for heat fluxes of heated materials are greatly desired for some practical application. However, there have been little technique to meet such requirements.

Ultrasound, because of its high sensitivity to temperature, has the potential to be an effective means for measuring temperatures and some works on the ultrasonic temperature estimations have been made extensively.[1-7] Since temperature and heat flux are closely related each other, it is highly expected to determine heat fluxes from temperature information. Recently, an attempt has been made to determine heat flux of a heated material from ultrasonic pulse echo measurements.[8] In the attempt, the heat flux at an accessible surface must be known so that unknown heat flux could be determined.

In this work, an ultrasonic method to determine transient heat flux through a heated surface of a material is proposed. In the determination, the ultrasonic thermometry providing temperature distribution measurements[4-7] is effectively utilized. It is noted that heat flux can be determined from ultrasonic pulse-echo measurements with a single ultrasonic transducer and there is no need to know any heat flux at an accessible surface where the ultrasonic transducer is installed. To demonstrate the feasibility of the proposed method, an experiments with a single-side heated steel plate has been made.

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2. Heat Flux Determination by the Ultrasonic Thermometry

We consider a solid material whose single side is heated and ultrasonic pulse-echo measurements are applied to the heated material. Assuming a one-dimensional temperature distribution in the single-side heated material, the transit time of ultrasound in the direction of the temperature distribution can be given as a function of the temperature distribution. Therefore, it is possible to determine the temperature distribution from the transit time if any appropriate inverse analysis could be performed together with appropriate boundary conditions. Fortunately, the ultrasonic thermometry[4-7] enables us to determine such internal temperature distribution of heated materials. The detailed procedures of determining the temperature distribution is described in references.[4-7] It is noted here that not only the internal temperature but also surface temperature at the heating surface can be obtained by the ultrasonic thermometry. Thus, temperature gradient near the heating surface can be monitored nondestructively as long as the ultrasonic pulse echo measurements are being conducted.

We then consider to estimate heat flux through the heating surface. Such heat flux q in the x direction which is the same direction as the temperature distribution is generally expressed as following equation by Fourier's low [9]

$$q = -k\frac{dT}{dx}, \qquad (1)$$

where k is thermal conductivity and dT/dx is temperature gradient near the heating surface. If the thermal conductivity is known, heat flux can be determined from the temperature gradient. Such temperature gradient can quantitatively be obtained from the temperature distribution near heating surface determined by the ultrasonic thermometry. Thus, the heat flux through the heated surface and its variation can quantitatively be monitored as long as the temperature determinations by the ultrasonic thermometry is continued.

3. Experiment and Result

Figure 1 shows a schematic of the experimental setup used. This system provides simultaneous measurements of ultrasonic pulse-echoes and temperatures. A steel plate (JIS type: SKD) of 30 mm in thickness is used as the specimen and its bottom surface is heated by contacting with a copper plate (heater) which is heated by a gus burner and followed by forced cooling with a coolant spray. A shear wave transducer of 5 MHz is installed on the top surface and ultrasonic pulse-echo measurements are made for obtaining ultrasonic transit time through the steel plate. The ultrasonic echoes are acquired every 0.02 s with a PC-based real-time acquisition system. The transit time of the ultrasonic echo from the bottom is precisely determined and then used for the ultreasonic thermometry to determine temperature distribution near the bottom surface of the steel. Temperaure at the upper surface of the steel is used as a boundary condition in the thermometry. Once the temperature gradients near the bottom surface are determined, heat fluxes are then determined from Eq. (1).

Figure 2 shows the variation in the estimated heat flux during heating and cooling. In this estimation, thermal conductivity k=30.5 W/(m・K) is used. It is observed in Figure 2 that the heat flux rapidly increases just after heating started and then gradually desreases due to natural cooling and rapidly decreases by forced cooling and then gradually increases due to natural heating, with the elapsed time. The heat flux estimated by ultrasound almost agrees with that measured using a conventional thin-type heat flux sensor inserted between the steel and copper plates. Thus, it has been demonstrated that the proposed ultrasonic method does woek properly for monitoring heat flux through the heating surface.

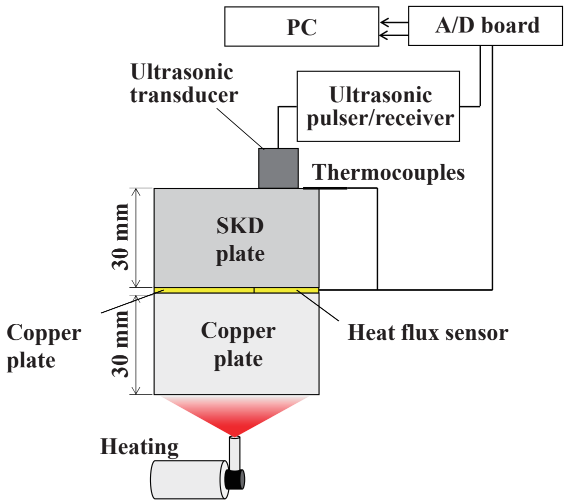

Fig. 1 Schematic of the experimental setup.

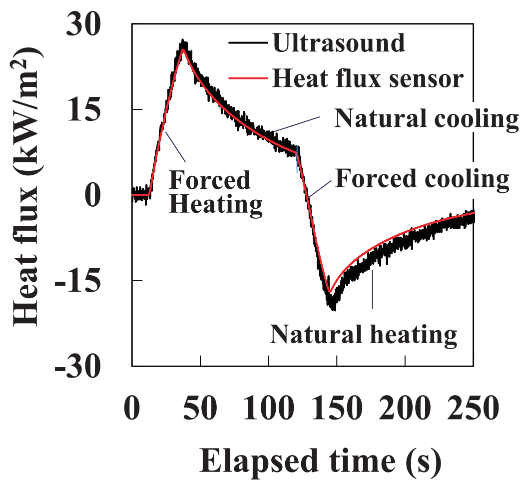

Fig. 2 Variations of the estimated heat fluxes through the heating surface with the elapsed time.

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