1Pb2-4

Improvement of Spatial Resolution in Temperature Profiling inside Materials by Ultrasound

超音波による物体内部の温度プロファイリングにおける空間分解能の向上

Kamui Yoshida [1†], Naoki Wadamori [2], and Ikuo Ihara [2]
([1] Grad. School of Nagaoka Univ. Tech.; [2] Nagaoka Univ. Tech.)
吉田　龍立 [1†]，和田森　直 [2]，井原　郁夫 [2] ([1] 長岡技術科学大学大学院, [2] 長岡技術科学大学)

1. Introduction

Because temperature is an important factor related to the strength and behavior of various materials, there are strong demands for non-destructive measurements of temperature distributions inside materials during their heating processes. In order to meet such demands, the authors had developed and validated ultrasonic thermometry providing internal temperature profiling for heated materials[1-3]. The method basically consists of the ultrasonic pulse-echo measurements and heat conduction analysis with a finite difference method. Although this method has unique potential as a temperature monitoring method, further improvements in spatial resolution and time responsiveness are desired for the practical use. In this work, to meet such requirements in the ultrasonic thermometry, moving averaging in acquiring ultrasonic signals has been made and a heat conduction analysis based on an implicit method has been proposed. Their effectiveness in the thermometry has been demonstrated through experiments with a heated steel.

2. Method

2.1 Waveform acquiring with moving averaging

The ultrasonic thermometry proposed by the authors can effectively determine the temperature distribution inside and on the surface of a heated material, by combining heat conduction analysis and ultrasonic pulse echo method[1-8]. In the heat conduction analysis, a finite difference analysis is employed and temperature distributions are quantitatively determined by the explicit method using the forward time centered space scheme (so-called FTCS scheme). In the analysis, the condition of $h > \sqrt{2\alpha\tau}$ must be satisfied to be able to obtain stable analysis results, where h is the grid spacing of the difference model (corresponding to the spatial resolution of the resulting temperature distribution), α is the thermal diffusivity of the measurement object, and τ is the time step (related to the time response in the temperature determination). Therefore, in order to improve the spatial resolution in the ultrasonic thermometry, it is quite necessary to shorten the τ corresponding to the interval of waveform acquisition in ultrasonic pulse echo measurements. On the other hand, to improve the precision in determining temperature, it is indispensable to measure ultrasonic propagation time precisely. Such precise propagation time could be obtained if appropriate ultrasonic waveforms having higher signal to noise ratio (SNR) could be used in the propagation time determination. Noise reduction due to averaging of measured waveforms should be effective to improve the SNR. Thus, to achieve both shorter interval of waveform acquisition (shortening τ) and higher SNR of the measured signal, so-called time moving averaging in the waveform acquisition has been applied to the ultrasonic thermometry.

2.2 Heat conduction analysis by implicit method

We consider a temperature profiling inside a thick plate whose single side is being heated. Since the above-mentioned FTCS scheme was used in the heat conduction analysis in the ultrasonic thermometry, the accuracy in determining the heating surface temperature is strongly affected by the deviation of the ultrasonic wave propagation time, and the effect extends over a wide region of temperature distribution from the heating surface to the interior. In order to overcome this problem, a temperature analysis by the Crank-Nicolson method[9] which is one of the implicit methods, is applied to the ultrasonic thermometry. It is highly expected by applying such method that not only less effect from the deviation of the ultrasonic propagation time but also improvement of spatial resolution in temperature profiling.

3. Results

To demonstrate the effectiveness of using the modified method mentioned above, an experiment with a single-sided heated steel plate has been made as shown in **Fig. 1**, where the temperatures inside and on the surface of the steel plate are determined by the ultrasonic thermometry based on ultrasonic pulse-echo measurements. **Fig. 2** shows variations in the estimated surface temperatures with the elapsed time. It is noted that the measurements are being made during no heating. It can be seen that the scattering in the surface temperature estimated by the proposed method is smaller than that by the former method, as expected. **Fig. 3** shows the temperature distributions inside the heated steel measured at 70 ms after the heating starts. The spatial resolution of the proposed method is much better than that of the former method. This is basically because the resolution in the former method is limited by the stability condition due to the FTCS scheme. In addition, a certain fluctuation in the estimated temperature values near the heating surface is observed in the former method while the fluctuation by the proposed method is relatively small. Thus, it has been demonstrated that the proposed thermometry provides appropriate stable temperature profiling.

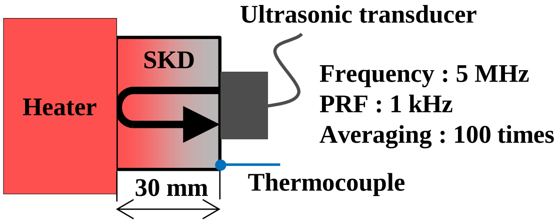

Fig. 1 Experimental setup for internal temperature profiling based on ultrasonic pulse echo measurements for a single side heated steel.

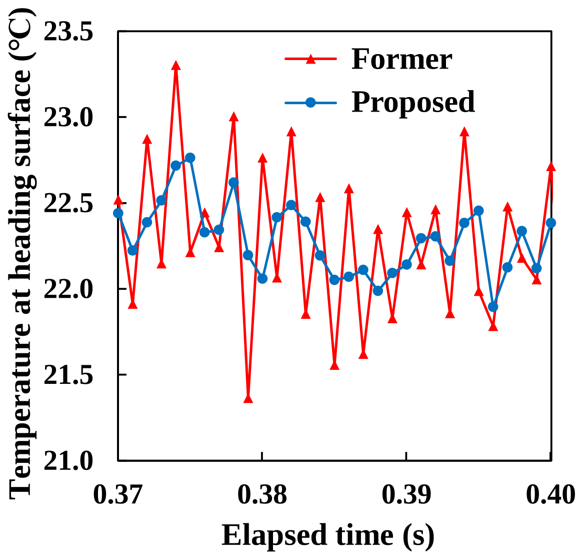

Fig. 2 Variations in the estimated surface temperatures with the elapsed time.

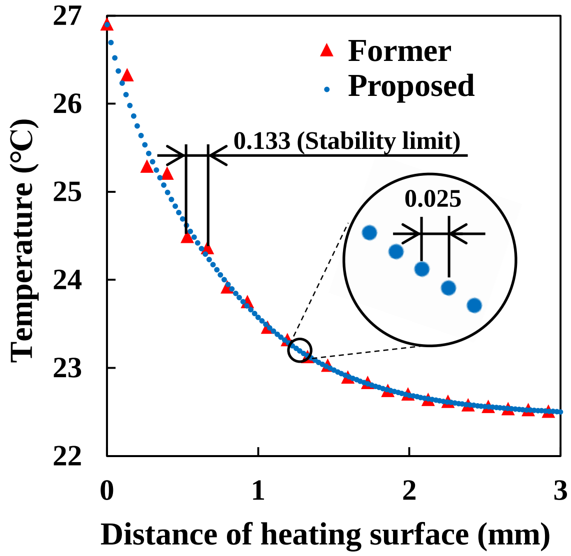

Fig. 3 Temperature distributions inside the heated steel measured at 70 ms after the heating starts.

Acknowledgment

This work was supported by JSPS KAKENHI (Grant-in-Aid for Scientific Research (B) 19H02477).

References

1. M. Takahashi and I. Ihara: Jpn. J. Appl. Phys. **47** (2008) 3894.
2. M. Takahashi and I. Ihara: Modern Physics Letters B, **22** (2008) 971.
3. I. Ihara and M. Takahashi: Int. J. Intelligent Systems Technologies and Applications, **7** (2009) 80.
4. M. Takahashi and I. Ihara: Jpn. J. Appl. Phys. **48** (2009) 07GB04.
5. H. Yamada, A. Kosugi and I. Ihara: Jpn. J. Appl. Phys. **50** (2011) 07HC06.
6. A. Kosugi, I. Ihara, and I. Matsuya: Jpn. J. Appl. Phys. **51** (2012) 07GB01.
7. A. Kosugi, Y. Ono, I. Matsuya, and I. Ihara: Journal of Physics: Conference Series **520** (2014) 012015.
8. I. Ihara, R. Sawada, Y. Ogawa, and Y. Kawano: *Advances in Condition Monitoring and Structural Health Monitoring, Lecture Notes in Mech. Eng.* (Springer Nature Singapore, 2021) p.789.
9. S. E. Fadugba, O. H. Edogbanya and S. C. Zelibe: Int. J. Appl. Mathematics and Modeling IJA2M. **1** (2013) 8.