PRECISION COMPUTERIZED TOMOGRAPHY FOR VISUALIZATION OF TEMPERATURE DISTRIBUTION USING AN ACOUSTIC DELAY LINE OSCILLATOR

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Abstract

In this study, we proposed an acoustic computerized tomography(A-CT) for visualization of temperature distribution using an acoustic delay line oscillator which is composed of 40 kHz-transmitter, -receiver and linear amplifier.

A projection data of temperature distribution with 120-sampling data can be acquired by linear scanning of the 2.5 mm-step of the probe. 30 projection data was measured by rotational scanning in the step of 6-degrees. The visualization area of the A-CT is a small size of 200 x 200 mm^2. Temperature distribution of the area is formed by a 30 W-electric heater with a diameter of 7.5 mm. The temperature distribution measured by the A-CT system was good agreement with the temperatures measured by thermocouples. Peak temperature of about 35 degrees Celsius and uniform temperature of 25 degrees Celsius were also able to measure each other.

Introduction

Measurement system which acquires phase information of the space using property of acoustic wave plays the important role in wide fields such as metrology,[1-7] environmental engineering,[8-14] meteorology[15-17] and agricultural science.[18,19] The measuring objects are also diversity such as humidity,[1] temperature,[2-19] wind velocity and wind direction. Above all, measuring a temperature distribution is required for low-pollution and energy saving. It is very available to measure using the acoustic wave in respect of noncontact measurement.[2,4,5,8-14,17,18] The comparatively sensitive measurement of a variation of temperature can be realized, when delay line oscillator is used, even if it is a simple system component.[6,7,20-22]

In this paper, we proposed an acoustic computerized tomography(A-CT) for visualization of temperature distribution. All projection data for A-CT is measured as oscillation frequency using an acoustic delay line oscillator. This system allows the use of precise temperature measurement. The operational principle and experimental results are described in the following sections.

Principles

Acoustic delay line oscillator

Figure 1 shows a schematic diagram of a sound probe using an acoustic delay line oscillator which acquires information of the temperature distribution in space. An acoustic delay line oscillator is a closed circuit composed of speaker(SP), aerial delay line, microphone(Mic) and amplifier functions as the oscillator. The mean velocity of sound between the SP and Mic is measured as an oscillation frequency of the oscillator. Hence, the temperature is finally calculated from the oscillation frequency, since the sound velocity is dependent on the medium temperature. The following two equations are simultaneously satisfied, while the acoustic delay line oscillator operates with a stable oscillation.

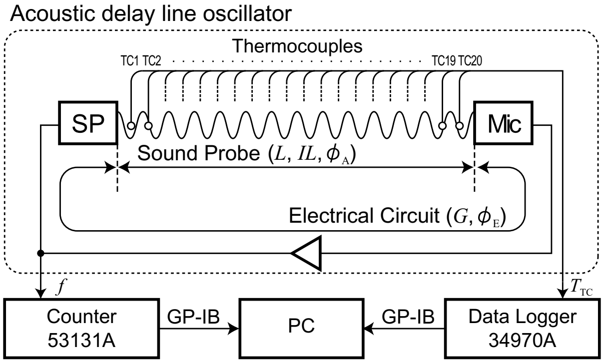


Figure 1 : Schematic diagram of a sound probe using an acoustic delay line oscillator composed of speaker (SP), aerial delay line, microphone (Mic) and amplifier. Mean velocity of the sound along the sound axis is measured as oscillation frequency of the delay-line oscillator.

$$G + IL \geq 0 \text{, (dB)} \tag{1}$$

$$\phi_A + \phi_E = 2n\pi \text{ ,} \tag{2}$$

here, G, IL, ϕ_A, ϕ_E and n are the gain of the amplifier, insertion loss of the acoustic delay line, acoustic phase delay, electric phase delay and order of oscillation, respectively. Equation (1) shows the amplitude condition in the oscillation of the positive-feedback circuit. Similarly, the frequency condition is shown in eq. (2).

Sound probe for temperature measurement

Although the amplitude condition is comparatively stable for the temperature, the frequency condition is sensitive. Hence, it is important to utilize the frequency condition in order to detect the temperature. The acoustic phase delay in eq. (2) is expressed by

$$\phi_A = \frac{2\pi fL}{c} \text{ .} \tag{3}$$

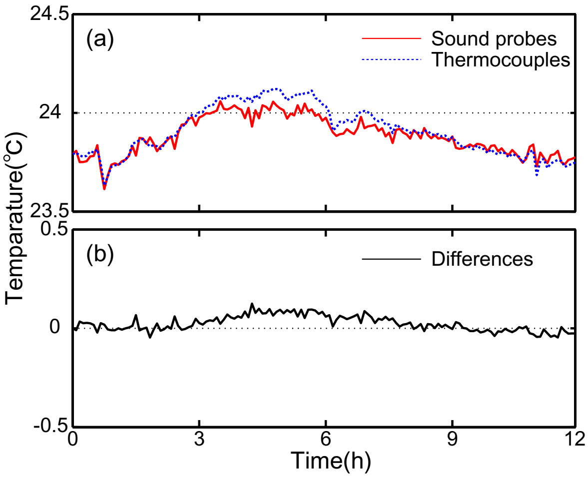


Figure 2 : Experimental results of space thermometry for 12 hours. A solid(red) line shown in (a) is temperature measured by a sound probe, and a broken(blue) line is mean temperature directly measured using 20 thermocouples. (b) shows differences between the temperature shown in (a).

when *c*, *f* and *L* are the mean sound velocity in the acoustic delay line, oscillation frequency of the circuit and length of the propagation path between SP and Mic, respectively.

In general, the sound velocity is defined by

$$c = 331.32\sqrt{\frac{\mathrm{T}_0 + T}{\mathrm{T}_0}}\,, \qquad (4)$$

where T_0 = 273.15K and T are the absolute temperature and the temperature of a minute space. By the arrangement of eqs. (2) – (4), the two following relations are obtained as one of the conditions of the electrical phase delay:

$$T_{mean} = \left(\frac{fL}{n}\right)^2 \frac{\mathrm{T}_0}{331.32^2} - \mathrm{T}_0\,, \quad \text{when } \phi_E = 0\,, \quad (5)$$

$$T_{mean} = \left(\frac{2fL}{2n-1}\right)^2 \frac{\mathrm{T}_0}{331.32^2} - \mathrm{T}_0\,, \quad \text{when } \phi_E = \pi\,. \quad (6)$$

T_{mean} is the mean temperature between the SP and Mic shown in Fig. 1. When circuit oscillation frequency *f*, the length of the propagation path *L* and order of oscillation *n* are substituted into eq. (5), the mean temperature T_{mean} is calculated. Therefore, the acoustic delay line oscillator functions as a "sound probe" which acquires the mean temperature of the space. Figure 2 shows experimental results of space thermometry for 12 hours. A solid line shown in Fig.2(a) is temperature measured by a sound probe, and a broken line is mean temperature directly measured using 20 thermocouples. Fig.2(b) shows differences between the temperature shown in Fig.2(a). The temperature measured by the sound probe is good agreement with the mean temperatures measured by 20 thermocouples.

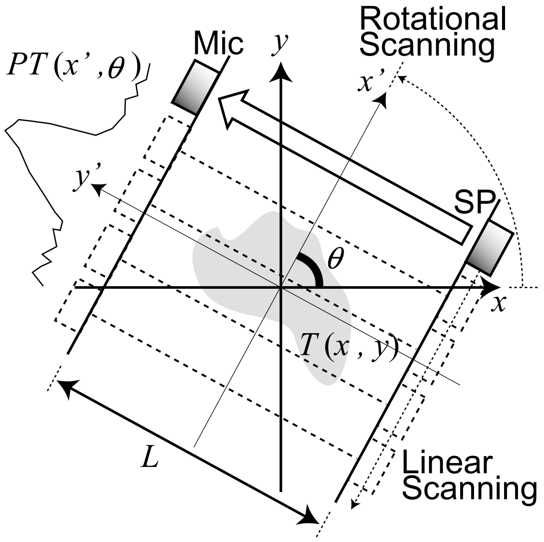


Figure 3 : Coordinate system of data acquisition system for A-CT using a compound-scanning system composed of linear scanning and rotational scanning.

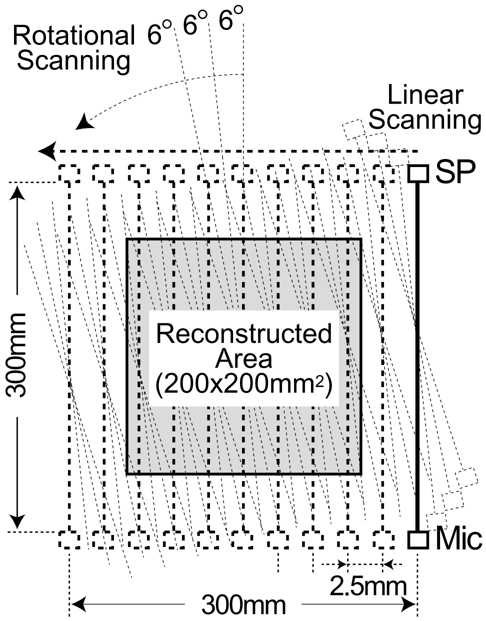
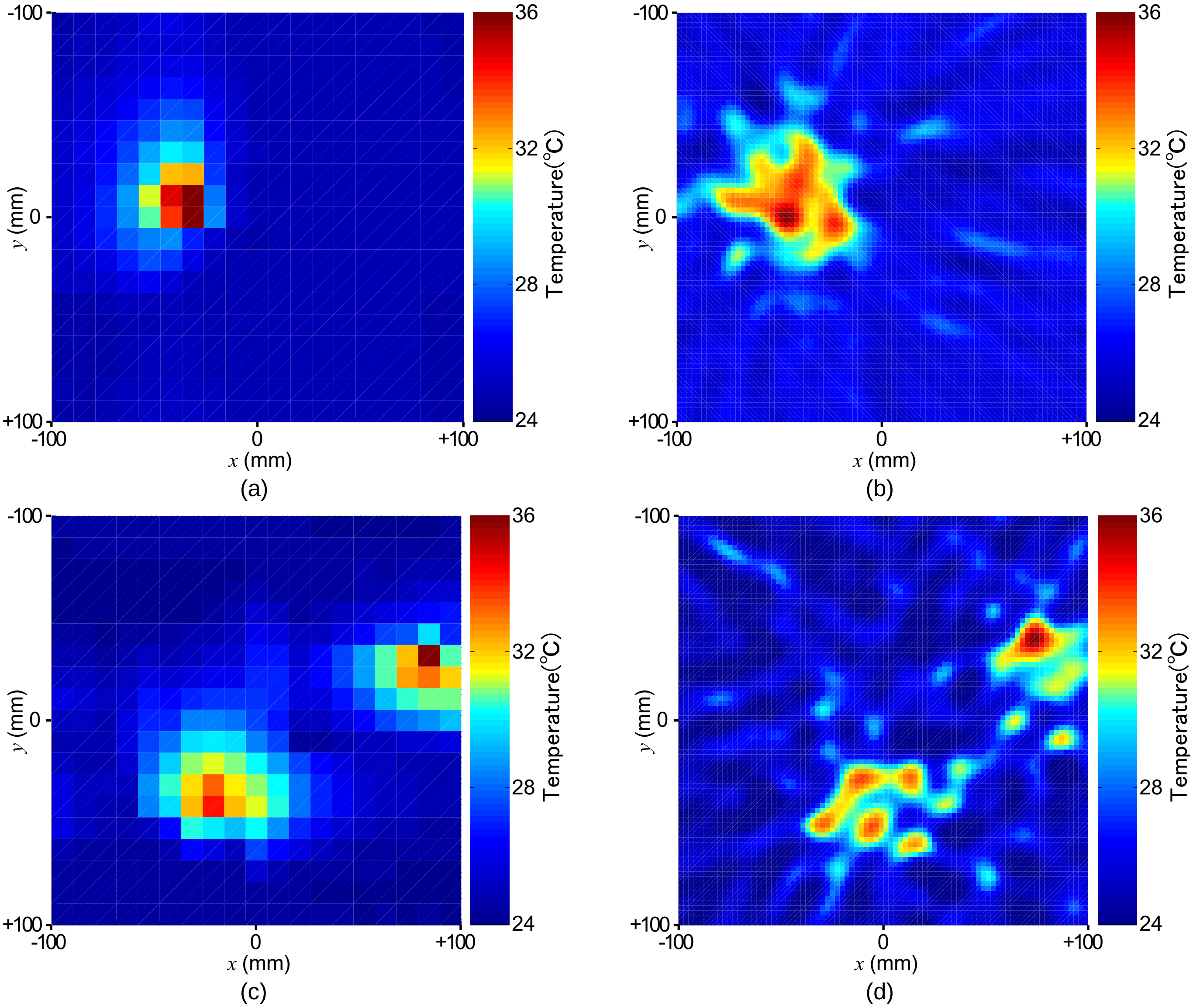


Figure 4 : Sound paths formed by the compound-scanning system. A projection data with 120 points is acquired by the probe every 2.5 mm while it moves along the straight line of 300 mm. In the rotation scanning by 6 degrees, 30 projection data for the A-CT are acquired.

Acoustic computerized tomography (A-CT)

Coordinate system of a data acquisition for the A-CT using a compound-scanning mechanism is shown in Fig. 3. The compound-scanning system is composed of linear-scanning and rotational-scanning. The area where distributed information of the temperature was acquired by the sound probe with the scanning mechanism and the area reconstructed by the



(a) (b)

(c) (d)

Figure 5 : Experimental temperature distributions measured by thermocouples [(a) and (c)] and a sound probe [(b) and (d)]. A heat source of (a) and (b) is located at (-50, 0))(mm) as (*x*, *y*). Heat sources of (c) and (d) are (-10, -50) and (80, 30) (mm) as (*x*, *y*).

CT method are correspondent. The mean velocity of sound is the result of curvilinear integral of the phase object along the sound axis, so it can be used for the CT. The projection $PT(x', \theta)$ of the phase object can be expressed as

$$PT\left(x',\theta\right)=\int T\left(x,y\right)dy', \qquad (7)$$

where $T(x, y)$ is two-dimensional temperature gradient. In this paper, the projected result of the phase object is experimentally obtained as the oscillation frequency of an acoustic delay line oscillator.

Sound paths established by the compound-scanning system are shown in Fig. 4. Projection with 120 measurement points is acquired by the sound probe every 2.5 mm while it moves along the straight line of 300 mm. 30 projection results per semicircle are obtained in the rotation scanning with a 6 ° . Hence, the total number of the sound paths is an 3600 (= 120 x 30). The reconstruction region is the circular space of radius 150 mm using convolution method. The display area in this paper is a square space of 200 x 200 mm^2 as a center of the reconstruction region.

Experimental Results and Discussion

System configuration

In the experiment, the sound probe operates at the frequency of 40 kHz using piezoelectric ultrasonic transducers, which are model T40-16 and R40-16/Nippon Ceramic Co., LTD, corresponding to the SP and Mic of acoustic delay line oscillator shown in Figs. 1, 3, 4. A sound has an acoustic delay line of 300 mm length as a sensor. The gain of the amplifier is 40 dB. The output of the delay-line oscillator is acquired as the oscillation frequency by a Agilent model 53131A universal counter with a time-averaging function. 20 thermocouples are installed for comparative measurements at 10 mm intervals along the propagation path, and temperatures are acquired by a Agilent model 34970A data logger. A 30 W electric heat source of 7.5 mm diameter is installed at a distance of 220 mm from the sound axis. The probe is installed in an x-θ mechanical stage controlled by a personal computer.

Visualization of temperature by A-CT

Figure 5 shows the experimental temperature distributions measured by thermocouples {(a) and (c)} and the sound probe {(b) and (d)}. Figures 5(a) and 5(c) are results of directly measured by mechanical scanning of a linear-thermocouple-array composed of 20 elements. Distributions shown in Figs. 5(b) and 5(d) are measured by compound-scanning with 120 sampling points per linear-scan and rotational-scan in 6 ° rotational steps, and reconstructed by the CT method. The display area of each figure is a square space of 200 x 200 mm^2 as a center of the reconstruction region. The heat source was aligned at (-40, 0)(mm) as (x, y) in Figs. 5(a) and 5(b). Heat sources of (c) and (d) are (-10, -50) and (80, 30)(mm). The peak values of the each temperature gradients shown in Figs. 5(a) and 5(b) are 36.0 and 35.8 degree, and in Figs. 5(c) and 5(d) are (33.9, 35.7) and (33.7, 35.2), respectively. In all results, the position of the heat sources and extent of the impact of the heat sources agreed approximately. Since it is reconstructed by the CT method, artifacts have appeared on the visualization images shown in Figs. 5(b) and 5(d). Using an A-CT, the temperature distribution which includes high temperature area of about 80 mm radius was realized with high resolution.

Conclusions

The precision two-dimensional temperature distribution was reconstructed by A-CT using an acoustic delay line oscillator. Acoustic delay-line oscillator has been used for the detection of sound velocity which is dependent on the air temperature, in order to sensitise and simplify the visualizing system.

As the experimental results showed that precision visualization was reconstructed using projection data in the sampling step of 2.5 mm and in the rotational step of 6 degrees. Non-contact visualization of the temperature distribution in a square space of 200 x 200 mm^2 which includes high temperature area of about 80 mm radius was realized with high resolution. The proposal method in this paper has the advantage that it can be used in such applications as reactor monitoring, atmospheric monitoring, and so on.

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