Temperature Field-monitoring Using Ultrasonic CT

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ABSTRACT

In order to effectively monitor the temperature field inside a building to prevent fire from happening in advance, a new non-intrusive measurement method of using ultrasonic CT is suggested in this paper. Being different with the conventional CT reconstruction, a kind of algorithm of using simultaneous equations analysis is employed to obtain CT reconstruction while projection data in the form of fan-beam is gathered by employing the directivity of ultrasonic sensor. The feature of this kind of algorithm is that it can perform CT reconstruction without using parallel projection data obtained by the conventional R-S (Rotation and Scanning) method. Both CT simulation and experimental results proves that the suggested CT algorithm is reasonable for monitoring temperature field and can be applied to the field of fire-detecting in the future.

KEYWORDS: ultrasonic CT, temperature field-monitoring, fire detection, simultaneous equation analysis, directivity of ultrasonic sensor

INTRODUCTION

Smoke detector and infra-ray detector are often used for initial fire-detecting inside a building. Since the detectors are not always located near the spot of the fire, as shown in Fig. 1, detecting time is needed when a fire is occurring. Therefore, it is essential to develop a method that can detect the location of the fire as quickly and accurately as possible at its initial stage.

CT (Computerized Tomography) is a kind of technique that can reconstruct the cross-sectional information from projection data [1-4]. The conventional image-reconstruction algorithm implemented on existing CT scanners requires the collection of X-ray data representing line integrals that are evenly spaced over a 360° range of angles. However when CT is suggested for temperature-monitoring inside a building, it is impossible to use the conventional R-S (Rotation-Scanning) method to collect parallel projection data for CT reconstruction because of the physical locations of the transmitters and the detectors. Also the projection data for CT reconstruction is collected only at limited projection angle [5]. Further, quick fire detection is especially needed for fire prevention. Therefore it is necessary to develop a new CT technique for quick fire detection with limited projection data.

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So far, we have proposed a ultrasonic CT method [6,7] to obtain the 3D temperature or CO_2-concentration distributions for environment field where ultrasonic phase differences are served as projection data. FBP (Filtered Back Projection)method was employed to fulfill the CT reconstruction based on the projection data over a 360-deg range of angles. Then we used iterative CT reconstruction algorithms of using inverse matrix transform to handle the limited angular parallel data for CT reconstruction [8].

The purpose of this study is to apply ultrasonic CT to measure the temperature distribution inside a building as a new fire-detecting method. In order to achieve this goal, a new CT reconstruction algorithm, based on simultaneous equations analysis, is suggested for CT reconstruction by using several ultrasonic transducers installed on the wall at one plane as shown in Fig. 2. Also the directivity of ultrasonic sensor is employed to get projection data without the need of the rotation of the detecting system, which can speed up the data-collecting time and void disturbing the temperature distribution to be detected. Projection equations were formulated and QR decomposition method is firstly suggested for solving those projection equations to fulfill CT reconstruction. Computer simulation of projection in the form of fan-beam and CT reconstruction process was conducted to verify the feasibility of the suggested CT reconstruction algorithm. An experimental system was established to empirically verify the possibility of the newly suggested CT reconstruction algorithm when applied to temperature measurement. During CT experiment, several ultrasonic transducers were mounted on the wall of a test chamber, inside which the heated discs formed the necessary temperature field to be measured. The phase difference of ultrasonic wave was detected as the projection data and processed by the computer code. Good agreement of the CT-reconstructed values with those obtained by thermocouple was confirmed.

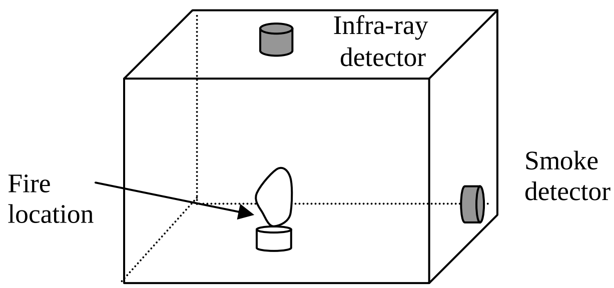


Fig. 1. Fire detection using smoke detector and infra detector.

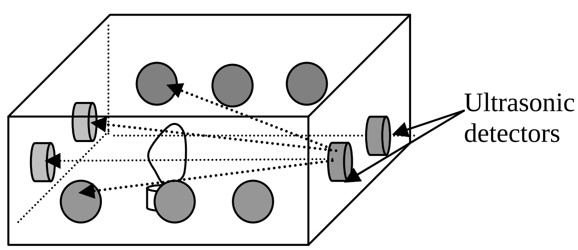


Fig. 2. Ultrasonic CT for fire detection.

TEMPERATURE-DETECTING USING ULTRASOUND

When ultrasound travels through air with temperature T, the sound speed of air c in the atmosphere is given by [9]

$$c = \sqrt{\kappa RT} \tag{1}$$

where κ and R are the specific heat ratio of air and the universal gas constant respectively. Now if there is a fire and the temperature of the thermal field changes from T_1 to T_2, the change of travel time Δt of ultrasound between transmitter and detector is

$$\Delta t = L \left(\frac{1}{\sqrt{\kappa RT_2}} - \frac{1}{\sqrt{\kappa RT_1}} \right) \tag{2}$$

where L is the distance between the transmitter and detector.

Then the correlation of temperature and phase difference is expressed as

$$\Delta \beta = \frac{2\pi fL}{\sqrt{\kappa R}} \left(\frac{1}{\sqrt{T_2}} - \frac{1}{\sqrt{T_1}} \right) \tag{3}$$

where f is the frequency of the ultrasound. With Eq. 3, if the change of phase difference is measured, the change of temperature is easily obtained.

Basic CT Reconstruction Principle

When ultrasound travels through a thermal space at an angle θ toward axis x where a temperature distribution exists, its sound speed changes accordingly. This fact inevitably leads to a change of phase difference between the ultrasonic transmitter and detector as shown in Fig. 3. The general phase difference $\Delta\beta = p(r,\phi)$ can be expressed as the summation of the local difference $\beta(x,y)=\beta(r,\phi)$ along the irradiation direction. That is

$$\Delta \beta = p(r,\theta) = \int_{-\infty}^{+\infty} \beta(x,y)\,du \tag{4}$$

where

$$x = r \cdot \cos\theta - u \cdot \sin\theta,\; y = r \cdot \sin\theta + u \cdot \cos\theta \tag{5}$$

By using FBP [2], the reconstructed two-dimensional distribution of ultrasonic phase difference can be written as

$$\beta(x,y) = \frac{a}{2n} \sum_{j=0}^{n-1} \sum_{k=-\infty}^{\infty} p(r_{jk},\theta_j) \times \Phi(x\cos\theta_j + y\sin\theta_j - r_{jk}) \tag{6}$$

where a is the ray spacing distance between parallel rays in each view and n is the number of views.

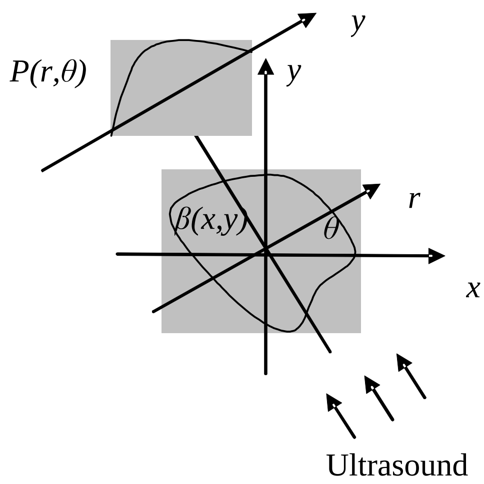


Fig. 3. Principle of CT.

From Eq. 6, it is known that, with the CT method, if the projected data $p(r_{jk},\theta_j)$ of the ultrasound phase differences are measured over a range of 0-360 degree, that is, $\theta=\theta_j=j\pi/n$, k=0,1,2…..; j=0,1,2…,n-1 in advance, the local phase difference $\beta(x,y)$ can be reconstructed by using a convolution method where Φ can be selectively defined for perfect reconstruction according to the actual situation.

So far, many methods have been proposed to obtain 2D distribution of $\beta(x,y)$ by mathematically handling the projection data from different angles over a range of 0-360°. Then stacking up the reconstructed 2D information will reconstruct a full 3D physical field. However, as for the non-parallel projection data, the newly suggested algorithm will be described in the next section

DATA ANALYSIS BASED ON SIMULTANEOUS EQUATIONS ANALYSIS

The simplified CT reconstruction model using simultaneous equations analysis is shown in Fig. 4.

The reconstructed plane is divided into a set of cells and projection rays from an transmitter passing through the plane and carrying the inner information out will be detected by several ultrasonic transducers.

If we establish a linear equation for kth ray passing through the plane using the form of

$$y = Ax + B \tag{7}$$

then the intersecting points of Eq. 7 on each cells will be obtained and the length between each pair of intersecting points along the line will be defined as L(i,j).

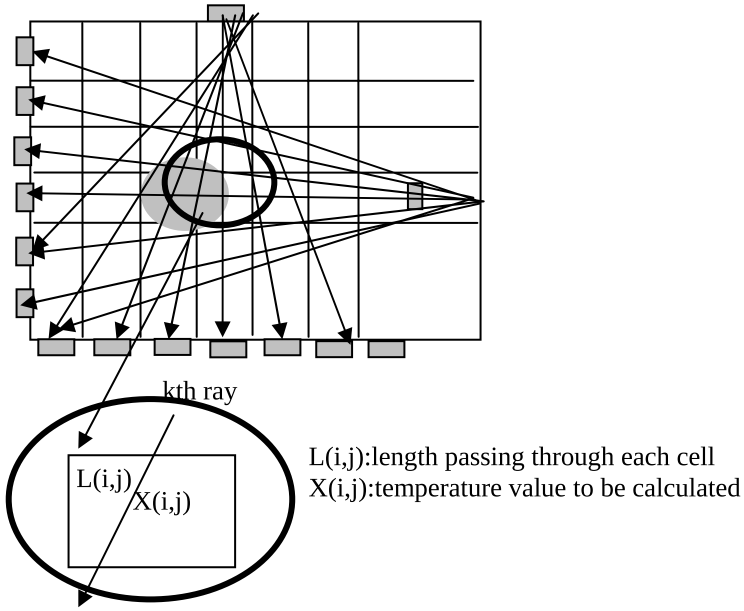


Fig. 4. CT reconstruction model using simultaneous equations analysis.

Assuming that the phase difference change between transmitter and transducer is along *k*th path is βk and the temperature value to be reconstructed is X (i,j), then by repeating all the projection process, the following simultaneous equations are obtained as

$$Lk_{11}X_{11} + Lk_{12}X_{12} + \cdots + Lk_{ij}X_{ij} = \beta k \tag{8}$$

Eq. 8 can also be expressed by using the following matrix

$$\begin{pmatrix} L1_{11} & L1_{12} & \cdots & L1_{ij} \\ L2_{11} & L2_{12} & \cdots & L2_{ij} \\ \vdots & & & \\ Ln_{11} & Ln_{12} & \cdots & Ln_{ij} \end{pmatrix} \cdot \begin{pmatrix} X_{11} \\ X_{12} \\ \vdots \\ X_{ij} \end{pmatrix} = \begin{pmatrix} \beta 1 \\ \beta 2 \\ \vdots \\ \beta n \end{pmatrix} \tag{9}$$

Based on Eq. 9, CT reconstruction process can be treated as a problem of finding the solutions for the set of simultaneous equations.

In this study, QR decomposition method is suggested to solve the above simultaneous equations and is shown in Fig. 5, the matrix X of $n \times m$ is decomposed as $X=QR$. Here Q is the orthogonal matrix and R the triangle matrix.

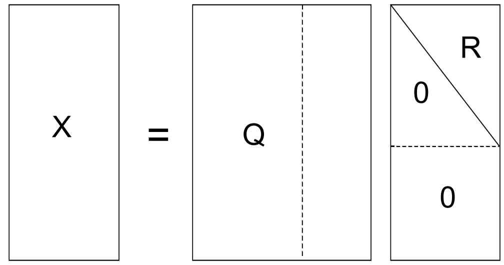


Fig. 5. QR decomposition method.

COMPUTER SIMULATION

In order to verify the newly suggested CT reconstruction algorithm, a set of computer codes of projection and CT reconstruction process was devised. A special Gaussian function [10] is used as the original image. During computer simulation, firstly the projection of the original image is obtained by employing fan-beam scanning process where the directivity is set to be 60° as the scanning range for ultrasonic sensor. Then by solving simultaneous projection equations to get the reconstructed image. The quality of the reconstructed image is evaluated by the similarity function defined as follows:

$$s=\left\{\sum_i\sum_j \rho_0(i,j)\cdot\rho(i,j)\right\}\Big/\left\{\sqrt{\sum_i\sum_i \rho_0(i,j)^2}\sqrt{\sum_i\sum_j \rho(i,j)^2}\right\} \tag{10}$$

where $\rho_0(x,y)$ and $\rho(x,y)$ are the densities of the original image and CT-reconstructed image respectively.

From Eq. 10, it is easy to know that s=1 means the perfect reconstruction while s=0 indicates the worst one. By calculating the similarity function, the reconstructed image's quality can be evaluated.

EXPERIMENTAL VERIFICATION

The experimental system setup for verification of the present CT algorithm is schematically shown in Fig. 6. From the ultrasonic transmitter located on the test chamber, ultrasound is transmitted at a fixed frequency and detected by ultrasonic detectors. The phase difference from the basic state where there is no temperature distribution is measured by a lock-in amplifier, then transferred to a computer through GPIB board as the general phase difference During CT experiment, 40 ultrasonic transducers that can be both used as transmitters or detectors (diameter 9.0 mm) were amounted on the wall of the test camber at an interval of 1 cm while an oscilloscope was used to monitor the change of the wave. The detecting range is set to be a space of 100× 100 mm. For each detecting process, projection data of the phase difference changes were traced for each projection path through a switch with high speed, then transferred to computer for CT reconstruction to obtain the local temperature distribution based on the CT method described above.

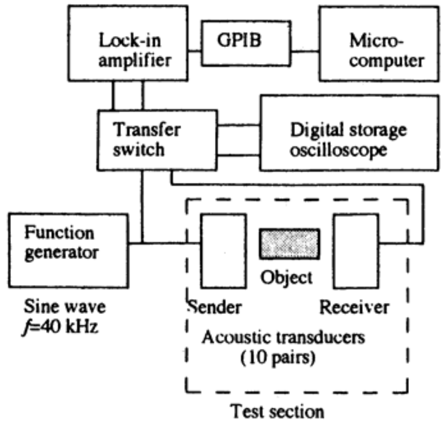
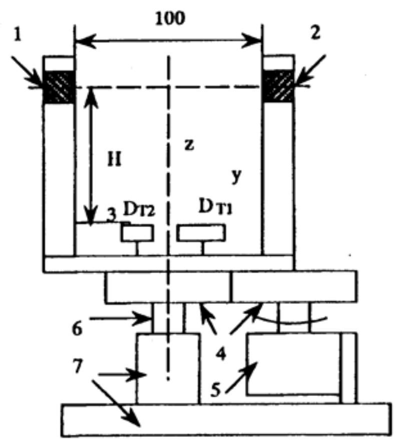


Fig. 6. CT experimental system setup.

Figure 7 shows the test chamber where the 3D asymmetric temperature distribution is formed. The test section consists of 2 heated discs, 10 transmitters and 30 ultrasonic detectors (frequency 40 kHz). The room temperature was 20°C. For the temperature reconstruction experiment, 2 electronic heater of a circular discs of D_1 = 30 mm and D_2=20mm in diameter, whose locations are 10 mm away from the center axis of the test chamber respectively, were used to form an asymmetric temperature field.



1 Ultrasonic transmitter	2 Ultrasonic detector
3 Electrically heated discs	4 Gear
5 Step-in motor	6 Thrust bearing
7 Base	

Fig. 7. Test Chamber for CT measurement of
3D temperature distribution.

Locations of ultrasonic transmitters and detectors in detail are shown in Fig. 8. Taking account of the directivity of the ultrasonic sensors and changing the position of the transmitters, a set of projection data is obtained without the need of rotation.

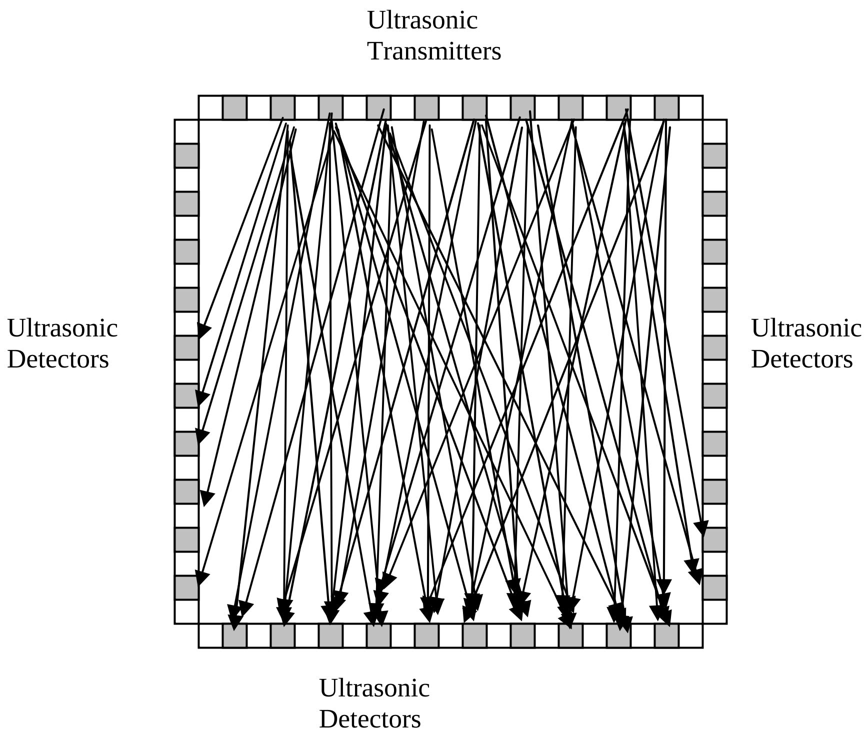


Fig. 8. Locations of ultrasonic transmitters and detectors.

With regard to the CT measurement, after the temperature distribution reached a steady state, and 300 projection equations data were gathered for CT reconstruction.

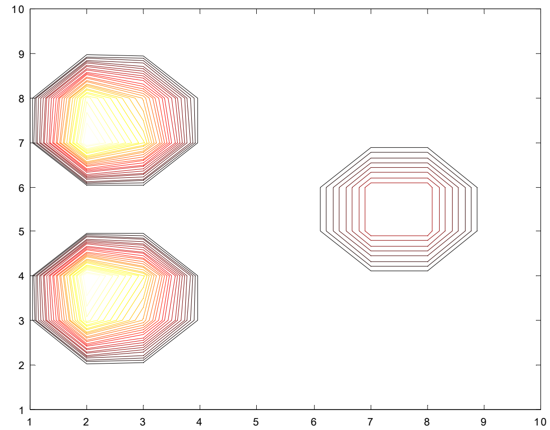
Finally, thermocouples were also used to measure the temperature distribution along the centerline of the asymmetrically heated region.

RESULT AND DISCUSSION

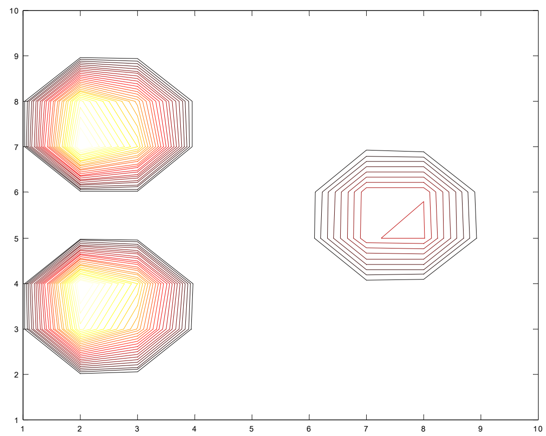
CT Computer Simulation

CT simulation result is given in Fig. 9a stands for the original image and Fig. 9b for the CT-reconstructed image by using QR decomposition method. With 300 projection equations collected, CT simulation was carried out. From Fig. 9a, it was confirmed that the original image was well reconstructed by the suggested CT algorithm, Further, it is also found that it only took 3 seconds to finish CT reconstruction, which is extremely practical for quick fire detection.

In Fig. 10, relation of similarity and the number of the projection equations is indicated. With more projection equations, the similarity will be relatively enhanced, which means the improvement of the reconstructed CT image.



(a) Original image



(b) Reconstructed CT image

Fig. 9. CT simulation results.

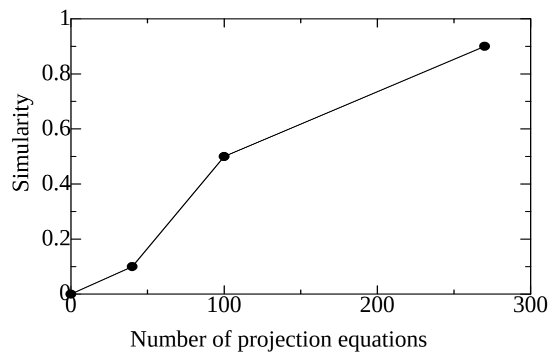


Fig. 10. Relation between number of projection equations and CT reconstruction similarity.

CT Experiment

Figure 11 gives the CT-reconstructed result of the temperature distribution for the plane of 100×100 mm. Though an asymmetric temperature was formed, the CT reconstruction algorithm could completely measure the temperature distribution. Further it was also demonstrated that the suggested CT method could be applied to detect the fire because the temperature increase and smoke generation accompanied with the fire would lead to the change of the ultrasound velocity. Even for a large-scale compartment, this method would still be effective on the condition that the ultrasonic projection data could be collected. Certainly, since ultrasound will attenuate if the detecting space is too large, in this case, measures to amplify the transmitted and the received ultrasonic signal are needed.

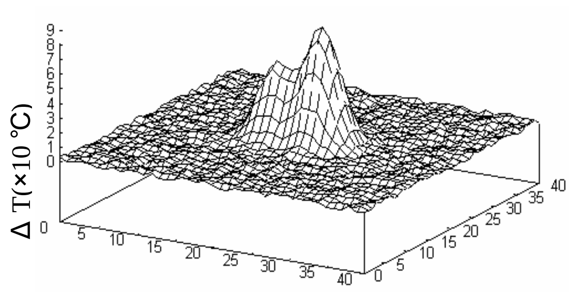


Fig. 11. Temperature distribution by CT reconstruction.

Figure 12 showed the temperature profiles obtained both by CT reconstruction and thermocouple along the centerline of the test chamber. From Fig. 12, though the maximum measuring error is found to be within 10%, good agreement between the CT-reconstructed temperature and those measured by thermocouples proved the validity of our CT-measuring system.

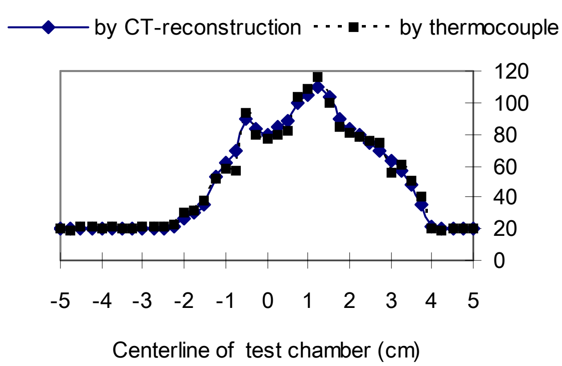


Fig. 12. Comparison of temperature profiles obtained by CT construction and thermocouple along centerline of test chamber.

CONCLUSIONS

In this research, a new CT reconstruction algorithm of using simultaneous equation is suggested for measuring temperature field by collecting projection data of ultrasonic phase difference on the basis of the directivity of ultrasonic sensor. As a result of CT computer simulation and experimental verification, some conclusions are obtained as follows:

(1) Computer simulation shows the improvement on similarity if the number of the projection equation is increased;
(2) Quick fire-detecting is possible because CT reconstruction only takes 3 seconds by using the computer code which was devised for this study;
(3) Through experimental CT reconstruction, it was confirmed that the temperature distribution was successfully reconstructed and CT-reconstructed temperature values were found to be in accordance with those measured by thermocouples.

Future work should be focused on differentiating between a temperature elevation from a fire and one from some kind of intended heat source.

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