Evaluation of Reconstruction Strategies of 3D Temperature Fields for Detecting Hotspots in Grain Bulk

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Abstract. A hotspot in a grain bulk is a localized high temperature zone and normally spoilage begins in this location. The reconstruction strategies of a 3D space are investigated to detect hotspots in grain bulk by acoustic tomography. Since the size of a grain silo is usually large, the whole space to be reconstructed is divided into three blocks and two reconstruction ways: whole reconstruction and block reconstruction, are considered. Three sound ray path selection rules including intra-block, generalized intra-block and unrestricted paths are investigated. These reconstruction ways and path selection rules are combined into four reconstruction strategies. To fully compare the abilities of these strategies in detecting hotspots in grain bulk, 2304 single-hotspot temperature fields and a three-hotspot temperature field are reconstructed by using noise-free and noisy travel-time data. Based on reconstruction results and difficulty in travel-time measurement, the strategy using whole reconstruction way and generalized intra-block paths is the optimal choice.

Introduction

The reconstruction of temperature fields based on acoustic tomography [1,2] uses the dependence of sound speed in materials on temperature along the sound ray path. For using this technique, several sound transmitters/receivers have to be arranged around the space of investigation such that the resulting sound ray paths cover the space as uniformly as possible. The space has to be subdivided into grid cells (i.e. pixels) with finite sizes. After sound travel-times along the selected sound ray paths are measured, the temperature field can be reconstructed by using an appropriate reconstruction algorithm. This technique has many advantages such as non-contact, easy maintenance, suitable for a large space. It has already been applied to the measurement of temperature fields in industry furnaces [3]. Recently, there has been considerable interest in applying acoustic tomography to monitoring temperature fields around seafloor hydrothermal vent [4] and in stored grain [5].

A hotspot in a grain bulk is a localized high temperature zone and normally spoilage begins in this location. When the grain goes out of condition, regardless of the cause, the temperature of stored grain increases. Grain has relatively low thermal diffusivity. Thus, compared with contact method, non-contact method is better for hotspot detection in grain bulk [5]. Stored grain can be considered as a porous medium. In stored grain, sound is propagated principally through the gas in the narrow passageways between the grain kernels. The temperature distribution of stored grain can be monitored via acoustic tomography [5].

Reconstruction of 2D temperature fields by acoustic tomography is often reported. But in many cases, for example, hotspot detection in grain bulk, reconstruction of 3D temperature field is needed. In this paper, the reconstruction strategies of a 3D space are investigated by numerical simulation for monitoring temperature field in a grain silo. Since the size of a grain silo is usually large, the whole space to be reconstructed is divided into three blocks and two reconstruction ways, that is, whole reconstruction and block reconstruction are considered. In grain bulk, sound is attenuated seriously as the sound propagating distance increasing. In order to ensure the accuracy of sound travel-time measurement, we had better avoid extra-long ray paths when we select sound ray paths. Three sound ray path selection rules, including intra-block paths, generalized intra-block paths, and unrestricted
paths are investigated. These reconstruction ways and path selection rules are combined into four reconstruction strategies.

Commonly used least-squares methods, such as direct matrix inversion algorithm, algebraic reconstruction technique (ART), simultaneous iterative reconstruction technique, multiplicative ART [6], require the number of pixels contained in measurement space to be less than that of the paths, which means the temperature fields reconstructed with these methods have a coarser spatial resolution. In this paper, radial basis function approximation and regularization are used in our reconstruction algorithm, which leads to the pixel number of the reconstruction image increasing dramatically.

In order to evaluate the reconstruction ability of different reconstruction strategies, 2304 single-hotspot model temperature fields and a three-hotspot model temperature field are reconstructed by using simulation data. The root-mean-square errors, hotspot temperature errors are used to evaluate the quality of the reconstructed temperature fields. Based on reconstruction results using noise-free and noisy travel-time data, the performances of these four strategies can be evaluated.

Theory of Acoustic Temperature Field Reconstruction

The sound speed $c$ in a gaseous medium at an absolute temperature $T$ can be expressed as $c = z \sqrt{T}$, $z$ is a constant decided by gas composition. In grain bulk, sound is propagated principally through the gas in the passageways between the grain kernels. The relationship between the sound speed $c$ in free space and the measured sound speed $c_m$ in grain bulk with the same gas and same temperature can be expressed as $c_m = c / \lambda$, $\lambda$ is the speed conversion coefficient of grain. $\lambda$ can be determined by calibration method [5].

Assuming the distribution of reciprocal of sound speed in the space can be $f(x, y, z)$, the sound travel-time $t_k$ along the path $l_k$ can be expressed as

$$ t_k = \int_{l_k} f(x, y, z) \, ds $$

where $m$ is the number of the selected sound paths.

Divide the space into $n$ voxels. $n$ is much greater than $m$ since high spatial resolution is required. Because of the complexity of real sound speed distribution, $f(x,y,z)$ cannot be represented by a functional expression, but can be expressed as the linear combination of a set of RBFs as follows.

$$ f(x, y, z) = \sum_{i=1}^{N} \sum_{j=1}^{k} \alpha_{ij} \phi_i(x, y, z) $$

where $x_i$, $y_i$, and $z_i$ are the geometric center coordinates of the $i$th voxel, $\alpha_{ij}$ is the coefficient to be determined, $\phi_i(x, y, z)$ is the RBF centered at $(x_i, y_i, z_i)$, $\alpha(\alpha > 0)$ is the shape parameter of the RBF. $\alpha$ decides the shape of RBF, affects the modeling accuracy of the forward problem and the ill-posedness of the inverse problem. Substituting Eq. 2 into Eq. 1, we have

$$ t_k = \int_{l_k} \phi(x, y, z) \, ds $$

Define $\varepsilon = (\varepsilon_1, \ldots, \varepsilon_N)^T, t = (t_1, \ldots, t_m)^T, A = (a_{ij})_{k \times n}$, we have

$$ A \varepsilon = t $$

The regularization solution of Eq. 4 can be expressed as

$$ \varepsilon = \sum_{j=1}^{p} \frac{u_j^T t}{\sigma_j + \mu / \sigma_j} v_j $$

where $u_j$ and $v_j$ are the left and right singular value vectors of matrix $A$, $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_p > 0$ are the singular values of matrix $A$, $p$ is the number of non-zero singular values, $\mu(\mu > 0)$ is the regularization
parameter. The regularization parameter $\mu (\mu > 0)$ controls the weights of measured data and experience in solution. If $\mu$ is too small, the noise in the measured data can't be well restrained. If $\mu$ is too large, the value of $\sigma_j + \mu / \sigma_j$ would be far away from $\sigma_j$, and the solution would lose much detailed information.

The selection of shape parameter value is related with the number of nodes in the grid and with the distance between them. When the positions of the acoustic transceivers and the grid division are determined, an proper shape parameter can be determined by using some approach, and the matrix $A$ and its singular value decomposition can be obtained. After obtaining the acoustic travel-time vector $t$ by measurement or simulation methods, the vector $g$, which describes the reciprocal distribution of sound speed, can be determined, and then the temperature distribution of the measured space can be calculated.

But so far, no matter the choice of the shape parameter $\alpha$ or the choice of the regularization parameter $\mu$ remains an open problem. No mathematical theory has been developed yet to determine its optimal value. Usually, they are determined by experience and numerical and experiments. In this paper, $\mu = 1e-8$.

Reconstruction Strategy

In this paper, the reconstruction strategies of a 3D space is investigated by numerical simulation for monitoring temperature field in a grain silo. The space to be reconstructed is $4.8m \times 14.4m \times 7.2m$, and the coordinates of its center are $(0.3, 0.3, 0.3)$. Since the dimension in y direction is large, the space is divided evenly into 3 blocks, and 48 acoustic transceivers (numbered 1~48) are amounted on its periphery in three planes, see Figure 1. Two reconstruction ways, i.e., whole reconstruction and block reconstruction are considered. Whole reconstruction means the reconstruction is conducted in the whole space at a time; while block reconstruction means the reconstructions are conducted in the three blocks separately.

![Figure 1. The space divided into three blocks and the arrangement of 48 transceivers.](image)

Any two transceivers forms a sound ray path. When a path contains multiple sound paths, short paths are selected. In this paper, three sound path selection rules, that is, intra-block paths, generalized intra-block paths, and unrestricted paths are investigated. These rules can be described as follows. 1) Intra-block path means the start and end of the path are located in the same block. 2) Generalized intra-block path means the length of the sound ray path isn't longer than the length of the longest intra-block paths. Intra-block paths belong to generalized intra-block paths. 3) Unrestricted path means there is no limit to the length of a sound ray path.

These reconstruction ways and path selection rules are combined into four reconstruction strategies as follows. 1) $s_1$, intra-block paths and block reconstruction are used. The temperature fields in block $\text{①}$, $\text{②}$ and $\text{③}$ are reconstructed from the sound travel-times along the 152, 113 and 152 intra-block paths respectively. 2) $s_2$, intra-block paths and whole reconstruction are used. The temperature fields in block $\text{①}$, $\text{②}$ and $\text{③}$ are reconstructed as a whole from the sound travel-times along the 391 intra-block paths. 3) $s_3$, generalized intra-block paths and whole reconstruction are used. The temperature fields in block $\text{①}$, $\text{②}$ and $\text{③}$ are reconstructed as a whole from the sound travel-times along the 523 generalized intra-block paths. 4) $s_4$, unrestricted path and whole reconstruction are used.
used. The temperature fields in block ①, ② and ③ are reconstructed as a whole from 760 sound travel-times.

Comparison of Reconstruction Strategies

To evaluate the reconstruction strategy quantitatively, two commonly used evaluation criteria of reconstruction quality, root mean squared error \( E_{rms} \) and hot spot temperature error \( E_{ht} \) are used in paper. They are defined as follows.

\[
E_{rms} = \frac{1}{n} \sum_{j=1}^{n} \left[ T(j) - \hat{T}(j) \right]^2 \times 100\% \quad j = 1, \ldots, n
\]

\[
E_{ht} = \frac{T_h - \hat{T}_h}{T_h} \times 100\%
\]

where, \( T_h \) and \( \hat{T}_h \) are the temperature of the true hot spot and reconstructed hot spot, \( T_m \) is the mean temperature of the model (true) field, \( n \) is the number of voxels, \( T(j) \) and \( \hat{T}(j) \) are the true and reconstructed temperature of the \( j \)th voxel. In this paper, the space to be reconstructed is discretized into \( 8 \times 24 \times 12 = 2304 \) voxels, each of size 0.6m \( \times \) 0.6m \( \times \) 0.6m.

In order to fully compare the abilities of these four reconstruction strategies in detecting hotspot in a grain bulk, 2304 single-hot temperature fields are reconstructed from noise-free simulated travel-times. The \( j \)th single-hotspot temperature field reconstructed can be expressed as

\[
T(x, y, z) = 293 + 60e^{\frac{2}{3}(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2} - 60e^{\frac{2}{3}(x-x_k)^2 + (y-y_k)^2 + (z-z_k)^2} - 60e^{\frac{2}{3}(x-x_l)^2 + (y-y_l)^2 + (z-z_l)^2} + 60e^{\frac{2}{3}(x-x_m)^2 + (y-y_m)^2 + (z-z_m)^2} + 60e^{\frac{2}{3}(x-x_n)^2 + (y-y_n)^2 + (z-z_n)^2} + 60e^{\frac{2}{3}(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2}
\]
Following can be seen from Figure 3 and Figure 4. 1) Although the bigger the standard deviation of noise, the bigger the reconstruction errors, the feature of temperature fields can be reconstructed correctly by any of s1 ~ s4. 2) No matter the travel-times are noise free or noisy, s3 and s4 can produce better reconstruction results than s1 and s2. This is mainly because more sound travel-time data are used in s3 and s4. Considering the difficulty in travel-time measurement, s3 is optimal since no extra long paths are used in this strategy.

Figure 4. Reconstruction errors under different reconstruction strategies and noise levels ($\delta=0$, 1e-5, 1e-4).

Conclusion

A hotspot in a grain bulk is a localized high temperature zone and normally spoilage begins in this location. In this paper, the reconstruction strategies of a 3D space are investigated to detect hotspots in grain bulk by acoustic tomography. Since the size of a grain silo is usually large, the whole space to be reconstructed is divided into three blocks. In grain bulk, sound is attenuated seriously as the sound propagating distance increasing, therefore extra long ray paths should be avoided to ensure the accuracy of sound travel-time measurement. Two reconstruction ways: whole reconstruction and block reconstruction; three sound ray path selection rules: intra-block, equivalent intra-block and unrestricted paths are considered. Based on extensive reconstruction results and difficulty in travel-time measurement, the strategy using whole reconstruction way and generalized intra-block paths is the optimal choice. On the one hand, such strategy can produce better reconstruction results since more sound travel-time data are used; on the other hand, the difficulty in travel-time measurement won't be big since no extra long paths are used.

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