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Dynamic reconstruction algorithm of temperature field based on Kalman filter

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Abstract. Development of temperature reconstruction algorithm plays an important role in the application of temperature field measurement by acoustic tomography. A dynamic model of temperature field reconstruction by acoustic tomography is established. A dynamic reconstruction algorithm based on Kalman Filter (KF) is proposed considering both acoustic measurement and the dynamic evolution information. An objective function fusing space constrain with dynamic evolution information is designed. Simulation results of three temperature field distribution models show that the reconstruction quality of dynamic reconstruction method based on KF is better than those of static reconstruction methods.

1. Introduction

Information of the temperature field distribution plays an important role in heat balance calculation, combustion efficiency evaluation, saving energy and reducing the pollution. Acoustic pyrometry technology is very important in many real industrial needs and applications because of the advantages as non-contact measurement, wide measuring range, easy for real time continuous measurement, convenient maintenance. The technology has been used in many areas, such as deep-sea hydrothermal temperature field measurement, industrial furnace combustion temperature field distribution for reconstruction and detection, atmospheric temperature field distribution measurement of the storage of grain temperature [1-3].

The classical reconstruction algorithms can be classified into two categories, i.e. two dimensional and three dimensional reconstruction algorithms. The main algorithms in two dimensional temperature field reconstruction are least squares[4-5], Fourier regularization method[6], gaussian function and regularization algorithm[7], algebraic reconstruction algorithm[8], Tikhonov regularization algorithm[9] etc.. The main algorithms of three dimensional temperature field reconstruction include the least square and SVD algorithm [10], CGLS and LSQR algorithms [11], methods based on RBF neural network [12], ART and SIRT algorithms [13], Tikhonov and TSVD regularization algorithm [14] and so on. The algorithms mentioned above only consider the measurement information and not focus on the temperature field dynamic information in dynamic process, it is more reasonable to adopt dynamic reconstruction algorithm to obtain the distribution of temperature field. A dynamic reconstruction algorithm is present to reconstruct the three-dimensional temperature field based on

Kalman filter (KF). The numerical simulation results show that this method can reconstruct temperature field more accurately than the static algorithms.

2. The principle and the static model of acoustic pyrometry

The basic principle of acoustic pyrometry is based on that the propagation speed of sound wave in gas medium is the function of gas temperature [15]

$$v = \sqrt{\frac{\gamma RT}{M}} = Z\sqrt{T} \tag{1}$$

Where v is the propagation speed of acoustic wave in gas medium, m/s; R is molar gas constant, J/mol.k; γ is gas specific heat ratio, T is the absolute temperature of gas, K; M is molar mass of gas, g/mol; Z = $\sqrt{\gamma R/M}$, it is a constant to specified gas.

Time of flight (TOF) that acoustic wave is propagated along a sound ray is represented

$$y_i = \int_{L_i} \frac{1}{v_j(x,y,z)} dl + n_i = \int_{L_i} f_j(x,y,z) dl + n_i \tag{2}$$

in which y_i represents the time of flight of the wave along the ith sound path; L_i is the transmission path of the ith sound wave ray; (x,y,z) is the location of units; $v_j(x,y,z)$ is the sound speed of the jth imaging unit; $f_j(x,y,z)$ is the slowness of the jth pixel units (i.e., the reciprocal of velocity), n_i is the measurement noise. Then the formula (2) can be simplified as static reconstruction model in the form of a matrix equation:

$$Y = AF + n \tag{3}$$

In which, A $\in R^{M\times N}$ represents the line segment length, $Y \in R^M$ is the TOF vector measured practically, $F \in R^N$ represents the space state factor, i.e. the reciprocal of velocity. M is the total of independent TOF measured across the temperature field, N is the number of pixels, $n \in R^M$ represents the noise vector in TOF measurement data. F is calculated by proper reconstruction algorithm, and then the temperature T(x,y,z) is obtained according to (4).

$$T(x,y,z) = \frac{1}{F(x,y,z)^2 Z^2} \tag{4}$$

3. Reconstruction method of three-dimensional temperature field based on KF

The inversion problem above is expressed as state estimation problem in time-varying estimation method [16]. It is assumed the measured value Y_k at moment t_k is obtained, where k is the discrete time step. The information provided is used to update the sate estimation at the moment t_k. It is also assumed the problem is discrete with time variable. The state equation describing the time evolution information of the temperature field and the measurement equation expressing the relationship between temperature field distribution and measured value are needed in state estimation problem. The time evolution information equation of the temperature field distribution T_k (or slowness distribution F_k) is shown in (5)

$$F_{k+1} = \mathrm{g}(F_k, w_k) \tag{5}$$

Where F_k is the slowness variable at moment k; g (.) describes the dynamic evolution information expressed by a series of partial derivative equations in temperature field measurement; w_k represents the uncertainty of the dynamic evolution equation; and subscript k is the discrete time index. Equation (5) can be approximated to a linear equation

$$F_{k+1} = B_k F_k + w_k \tag{6}$$

Where B_k is the evolution operator (state transformation matrix), equation (6) can be considered as pure random evolution model because there is not process dynamic information and B_k is assumed as a unit matrix. It is assumed w_k is Gaussian white noise and the covariance matrix determines the time evolution rate.

The measurement equation is

$$y_k = A_k F_k + n_k \tag{7}$$

A_k is measurement operator, n_k represents the uncertainty of dynamic evolution equation.

The estimation value can be calculated by minimizing following objective function at the assumption of Gaussian assumed condition

$$J(F_k) = \left\|F_k - F_{k|k-1}\right\|^2 + \left\|y_k - A_k F_k\right\|^2 \tag{8}$$

The recursion KF method is obtained by minimizing the objective function of (8) which consists of time updated equation (9) and (10) and measurement updated equation (11), (12) and (13).

$$F_{k+1|k} = B_k \cdot F_{k|k} \tag{9}$$

$$D_{k+1|k} = B_k \cdot D_{k|k} \cdot B_k^T + S_k^w \tag{10}$$

$$K_k = D_{k|k-1} \cdot A_k^T \cdot [A_k \cdot D_{k|k-1} \cdot A_k^T + S_k]^{-1} \tag{11}$$

$$F_{k|k=} F_{k|k-1} + K_k \cdot [y_k - A_k \cdot F_{k|k-1}] \tag{12}$$

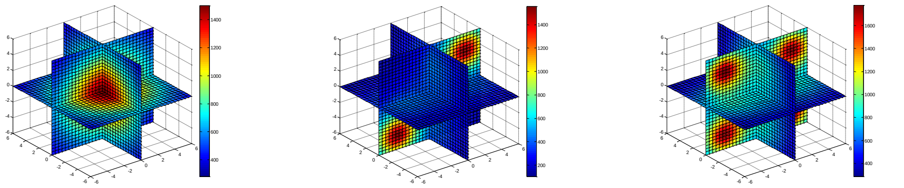
$$D_{k|k} = [I_N - K_k \cdot A_k] \cdot D_{k|k-1} \tag{13}$$

The estimation value $F_{k|k}$ of real state vector is obtained according to the recursive minimum mean square error by using initial value $F_{1|0}$ and $D_{1|0}$. The gain K_K can be calculated off-line in advance so that the calculation burden on-line is decreased as only (9) and (11) are needed to calculate on-line. The previous measurement data saved to estimate current state is decreased. Simple diagonal matrix is used to be the state and observation variance.

4. Numerical simulation of the reconstruction method of temperature field

Numerical simulation is adopted to verify the feasibility of the dynamic reconstruction algorithm based on KF, the reconstruction quality is compared with least squares, algebra reconstruction technique (ART) method. A 12 m×12 m×12 m cube space area is chosen and 20 acoustic sensors are arranged in three different planes respectively to obtain 58 the acoustic sound rays independently. The whole image reconstruction area is divided into 3×3×3=27 sub areas. The bicubic interpolation of 31×31×31 are obtained after getting the temperature in each subdomain.

Three classical temperature fields are chosen to simulate for verifying the feasibility of the proposed algorithm, which are single-peaked symmetric, double peak symmetric and four peak symmetric, the model temperature field distributions are shown in Fig.1.



(a) single-peaked symmetric (b) double peak symmetric (c) four peak symmetric

Figure 1. Diagrams of model temperature fields

The temperature field reconstruction results of least square method, ART and the dynamic algorithm based on KF are shown in Figure 2, Figure 3 and Figure 4. The reconstruction images show that three algorithms can reconstruct the distribution images according with model temperature field. Three errors are adopted to evaluate the reconstruction quality of three algorithms that are the maximum relative error E_1, average relative error E_2 and root mean square error E_3. The maximum relative error, relative error of the mean and the root mean square error are defined as (14), (15) and (16).

$$E_1 = \frac{|T_{M\max} - T_{R\max}|}{T_{M\max}} \times 100\% \tag{14}$$

$$E_2 = \frac{|T_{Ma} - T_{Ra}|}{T_{Ma}} \times 100\% \tag{15}$$

$$E_3 = \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}[T_M(j) - T_R(j)]^2}}{T_{M\max}} \times 100\% \tag{16}$$

where N is the number of pixels in reconstructed temperature field; T_M (j) is the average temperature of model temperature field; T_{Mmax} is the maximum temperature of pixels in model temperature field; T_R (j) is the temperature of pixels in reconstructed temperature field, T_{Ra} is the average temperature in reconstructed temperature field; T_{Rmax} is the maximum temperature of pixels in reconstructed temperature field.

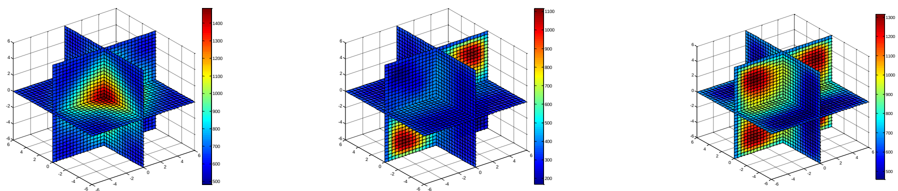


Figure 2. Diagram of reconstructed temperature field by least squares

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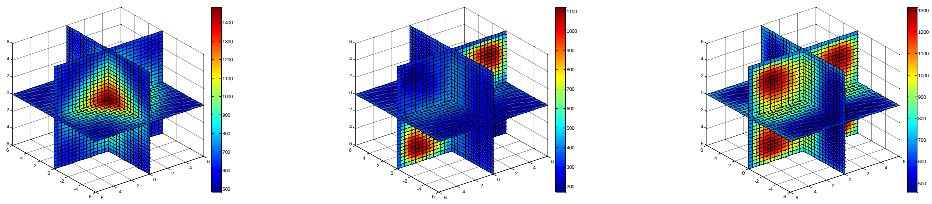

Figure 3. Diagram of reconstructed temperature field by ART

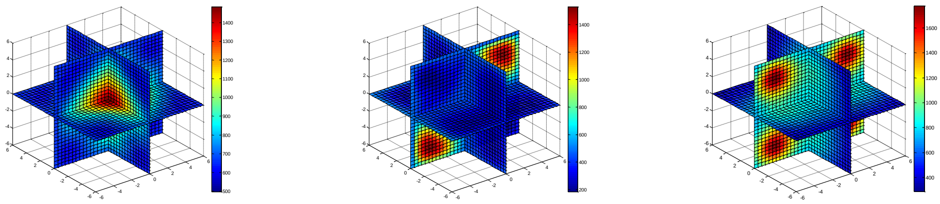

Figure 4. Diagram of reconstructed temperature field by dynamic reconstruction algorithm

The root mean square error of reconstruction by least square reconstruction for three model temperature fields that are single-peaked symmetric, double peak symmetric and four peak symmetric temperature field are 0.0389, ,0.0845 and 0.1256 respectively. The root mean square error of ART method are 0.0335, 0.0812 and 0.1232 respectively. The root mean square error of dynamic reconstruction method bases on KF are 0.0126, 0.0438, and 0.0755 respectively. The image quality is improved by adopting the dynamic reconstruction method.

5. Conclusion

The measurement technology of temperature field by acoustic tomography is attached important to widely. The reconstruction algorithm plays an important role in temperature field reconstruction by acoustic technology which affects the reconstruction accuracy and practicability. The past algorithms focus on static reconstruction, but the temperature field is the object varying with time. The dynamic reconstruction algorithm of temperature field based on KF is proposes and simulation has been carried out with three typical temperature fields. The results show that the precision of algorithm based on KF is increased significantly compared with those of the least squares and ART algorithm. It provides a highly effective method for acoustic temperature field reconstruction.

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