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A double decentralized fuzzy inference method for estimating the time and space-dependent thermal boundary condition

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ABSTRACT

For the inverse heat conduction problem to estimate the time and space-dependent thermal boundary condition, a double decentralized fuzzy inference (DDFI) method with a temporal-spatial decoupling characteristic is proposed. A set of decentralized fuzzy inference modules (DFIMs) corresponding to the temperature measurement points are established. Each DFIM contains a set of decentralized fuzzy inference units (DFIUs), and each DFIM performs the fuzzy inference process from the vector of time series of temperature measurements at the corresponding temperature measurement points. The inference results of DFIUs in the time domain are weighed and synthesized by dynamic response coefficients to obtain the time adjustment vector of the thermal boundary condition. In the space domain, the inference results of DFIMs are weighed and synthesized by the normal distribution function to obtain the space adjustment vector. Numerical experiments are performed to study the effects of the number of measurement points, measurement errors and the buried depth of thermocouples on the inversion results. Comparison with the existing dynamic matrix control inverse method is also conducted, and it shows the validity of the inverse method established in this paper.

1. Introduction

The inverse heat transfer problem (IHTP) is the estimation of the unknown characteristic parameters, such as boundary conditions, thermal physical parameters, geometry shape, initial condition, the source term, by using the internal or surface temperature measurements in the heat transfer system. In recent years, the IHTPs have been studied extensively due to their applications in various engineering fields, such as power engineering [1], aerospace engineering [2], materials processing [3], metallurgical engineering [4], nondestructive testing [5,6], bioengineering [7], military industry [8].

Many research results on the steady inverse heat transfer problems based on various optimization techniques have been reported. Duda and Taler [9] applied the Levenberg-Marquardt method to determine the fireside heat flux, heat transfer coefficient on the inner surface and temperature of water-steam mixture in water-wall tubes. Yu and Luo [10] proposed a modified Levenberg-Marquardt method for estimating heat transfer coefficients and heat flux of the billet surface in continuous casting. Huang et al. [11] applied the steepest descent method to estimate the local heat transfer coefficients of plate finned-tube heat exchangers. Huang and Chao [12] applied the conjugate gradient method to detect the unknown irregular boundary shape. Chen and Yang [13] applied the conjugate gradient method to estimate the unknown space-dependent heat flux at the roller/workpiece interface during rolling process. Divo et al. [14] utilized the genetic algorithm to characterize the space-dependent conductivity of heterogeneous materials.

The sequential function specification method (SFSM) proposed by Beck et al. [15] has been used widely in the unsteady inverse heat conduction problems. Yang [7] applied the SFSM to estimate thermal boundary conditions of the biological tissue. Zhang et al. [16] applied the SFSM to estimate the heat flux distribution in the casting direction of the mold in the continuous casting simulator. Volle et al. [17] utilized the SFSM to recover the surface heat flux of the rotating cylinder during jet cooling. Wang et al. [18] used the SFSM and the sequential quadratic programming method to estimate the transient heat flux on the interface between bone and grinding tool. Meresse et al. [19] used the SFSM to identify the heat flux on the disc friction ring on a High-Speed Tribometer.

For the unsteady heat conduction system, Wang et al. [20,21] established an inverse method based on the dynamic matrix control (DMC) and realized the simultaneous estimation of several

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Nomenclature

c_p	specific heat, J·kg^{-1}·°C^{-1}
d	buried depth of thermocouples, m
e, $\boldsymbol{E}$	temperature deviation, deviation vector, °C
h	convection heat-transfer coefficient, W/m^2·°C
K	total number of time steps
L	length, m
M	number of measurement points
N	number of inverse points
p_e	range of the input variable, °C
p_u	range of the output variable, W/m^2
q, $\boldsymbol{q}$	heat flux, heat flux vector, W/m^2
$\boldsymbol{Q}$	heat flux matrix, W/m^2
R	number of future time steps
t	time, s
T, $\boldsymbol{T}$	temperature, temperature matrix, °C
x, y	space coordinates, m

Greek symbols

γ	degree of membership
$\Delta\boldsymbol{Q}$	compensation matrix of the heat flux, W/m^2
Δt	time step size, s
$\Delta\boldsymbol{U}$	vector of the fuzzy inference results, W/m^2
η	average relative error of estimated heat flux
λ	thermal conductivity, W/(m·K)
$\boldsymbol{\Lambda}$	weighting matrix
ρ	density, kg/m^3
σ	standard deviation of the measurement error, °C
φ	space weighting coefficient
ψ	time weighting coefficient
ω	random number

Subscripts/superscripts

amb	ambient
cal	calculated
exa	exact
i, *j*	counting integer
k	time index
l	index of the fuzzy set
m	index of the measurement point
mea	measured
r	index of the future time step
s	weighting calculation about space
t	weighting calculation about time
x, *y*	space coordinates
0	initial

transient heat fluxes. The DMC inverse method does not demand an assumption of a specific functional form of the heat flux in the future time steps. The DMC significantly reduces the dependence of the solutions on the future observed information, and enhances the reliability of the inversion solutions.

The IHCP is a typical ill-posed problem [22], namely, the existence, uniqueness, and stability of the solutions are not all satisfied. Because of the inherent ill-posed characteristic of the inverse problem, the inversion results of the classical inverse algorithms would deteriorate significantly when the number of measurement points reduces or the temperature measurements contain large errors [23,24].

For the ill-posed characteristic of the IHCP, Wang et al. [24] proposed a decentralized fuzzy inference (DFI) method to solve the steady IHCP. Based on the qualitative knowledge during the heat transfer process, using the DFI method estimates the distribution of the thermal boundary condition and unknown boundary shape. Research results show [23,25–27] that the DFI method can successfully identify the thermal boundary condition, that it can significantly reduce the effect of the number of measurement points and the temperature measurement errors on the inversion results, and that the DFI method possesses excellent computational efficiency and a strong anti-ill-posed capability. The DFI method is only suitable for estimation problems of time-independent thermal boundary condition. For estimation problems of time and space-dependent thermal boundary condition, it is of great theoretical and practical significance to find a solution with good anti-ill-posedness and high computational efficiency.

For the IHCP to estimate the time and space-dependent thermal boundary condition, a double decentralized fuzzy inference (DDFI) method with a temporal-spatial decoupling characteristic is proposed in this paper. A set of decentralized fuzzy inference modules (DFIMs) corresponding to the temperature measurement points are established. Each DFIM contains a set of decentralized fuzzy inference units (DFIUs), and each DFIM performs the fuzzy inference process from the vector of time series of temperature measurements at the corresponding temperature measurement points. The inference results of DFIUs in the time domain are weighed and synthesized by dynamic response coefficients to obtain the time adjustment vector of the thermal boundary condition. In the space domain, the inference results of DFIMs are weighed and synthesized by the normal distribution function to obtain the space adjustment vector.

In this study, the unknown time and space-dependent thermal boundary condition is estimated by numerical experiments. The effects of the number of measurement points, measurement errors and the buried depth of thermocouples on the inversion results are discussed, and the comparison with the DMC inverse method is also conducted. Results show that the DDFI inverse method significantly reduces the demand of the number of temperature measurement points, enhances the anti-interference capability against the temperature measurement errors, and possesses a good anti-ill-posed character.

2. Two-dimensional transient heat conduction problem

Consider a two-dimensional transient heat conduction system shown in Fig. 1. Supposed that the left and the lower surface of the system are insulated, the right surface is exposed to a convection environment, the upper surface is heated by a distributive heat flux $q(x,t)$.

The governing equation, the initial condition and boundary conditions of the heat conduction system are as follows respectively:

$$\rho c_p \frac{\partial T(x,y,t)}{\partial t} = \lambda\left[\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2}\right], \quad 0 < x < L_x, \quad 0 < y < L_y, \quad t > 0 \tag{1}$$

$$T(x,y,t) = T_0 \qquad 0 \leqslant x \leqslant L_x, \quad 0 \leqslant y \leqslant L_y, \quad t = 0 \tag{2}$$

$$-\lambda \frac{\partial T(x,y,t)}{\partial y} = 0 \qquad 0 < x < L_x, \quad y = 0, \quad t > 0 \tag{3}$$