STATISTICAL IDENTIFICATION OF LOCAL HEAT-TRANSFER PARAMETERS

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This article examines an external inverse heat-conduction problem on determining thermal parameters which are variable over time and along a boundary.

Since mathematical models are generally inadequate for fully describing thermal processes, identification of the parameters of a thermal system (parametric identification) usually entails simultaneous solution of a problem of structural identification (refinement of the mathematical model itself). Naturally, the structural identification is the more complicated task. Thus, to reduce its importance in the overall problem, when constructing the model it is necessary to account as fully as possible for all internal relationships, thermophysical characteristics and external effects. In particular, in solving the internal inverse heat-conduction problem, it is best to determine not the mean values of the characteristics but values dependent on the space and time coordinates. The latter instance more accurately reflects processes actually occurring in objects with distributed parameters. Such processes are usually described by an imprecise structural model [1] which, in the most general formulation, is nonlinear and requires linearization — since it is necessary to construct transfer matrices to describe a nonsteady thermal process in the form of a dynamic recursion system.

When methods of statistical identification are used, it is expedient to also employ statistical linearization, entailing the best probability approximation of nonlinear relations by relations linearized on the basis of normalization of the laws of the distribution of random processes [2]. A simple and adequate course of action here is to replace the nonlinear part of the initial equation $f[X(\tau), U(\tau)]$ by the sum $A(\mathbf{m}_X, P_X, \tau)\mathbf{X}(\tau)+B(\mathbf{m}_X, P_X, \tau)\mathbf{U}(\tau)$, where m_X is the vector of the mathematical expectation of the random vector of state X; P_X is its covariant matrix. A more accurate linearized relation can be represented by the expression

$$A(\mathbf{m}_X, P_X, \tau)\,\mathbf{X}(\tau)+\mathbf{f}_0(\mathbf{m}_X, P_X, \tau)=A(\mathbf{m}_X, P_X, \tau)\,\mathbf{m}_X+B(\mathbf{m}_X, P_X, \tau)\,\mathbf{U}(\tau),$$

where f_0 is a vectorial statistical characteristic of nonlinearity, i.e., a function of the probability moments of the variables X_i. The norm of the vector $f_0 - Am_X$ is sufficiently small. The components of the matrices A and B and the vector f_0 can be found from the criterion of the minimum of the mean square error [3]. In the formulation being considered, the vector of state will include the desired local heat-transfer parameters, which vary along the boundary. It should be noted that, in identifying local parameters (such as heat-transfer coefficients variable over the contour of the investigated region), we deal with individual closed contour loops which are joined together into a single multiple-connected automatic control system. The number of loops, meanwhile, is determined by the number of sections of the surface being investigated within which the heat-transfer parameters are taken as constant. In other words, since determining the local boundary conditions requires making allowance for the correlations between all of the control loops, it is best to include characteristic temperatures of each of the investigated local regions in the measurement vector. Thus, the object function, which has to be constructed, should include all of the sought parameters and the results of temperature measurements.

Since the problem being examined is an imperfectly stated problem, some means must be provided to allow for regularization of the solutions obtained. Such means may include preassignment of the character of the sought relations (especially their constancy over time)

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TABLE 1. Identification of α, W/(m$^2\cdot$deg), of a Turbine Cooling Jacket

Parameters (mean)	T_1, °C	T_2, °C	T_3, °C	T_4, °C	α_1	α_2
Initial data	204	206	208	210	—	—
Results of identification	202,9	206,4	207	210,1	114	80

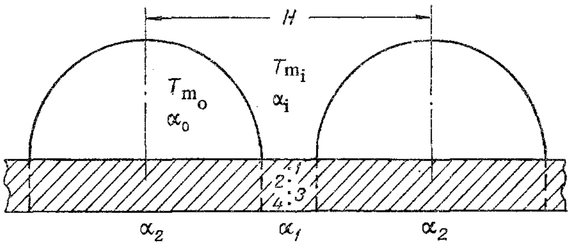

Fig. 1. Tube jacket of a cooled gas flue in a fluidized-bed furnace.

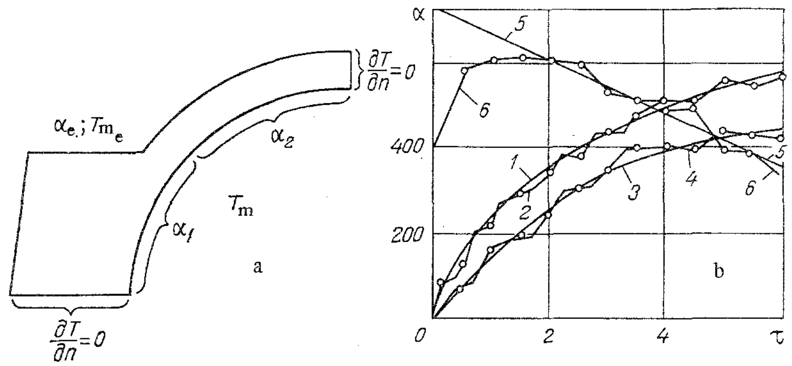

Fig. 2. Determination of a local heat-transfer coefficient on the inside surface of the casing of a steam turbine. τ, h; α, W/(m$^2\cdot$deg).

or limitations on the parameters of the algorithm (for example, having the number of iterations in the iteration process correspond to the error of the initial data). We will demonstrate the above-described approach to solving imperfectly stated problems using the example of realization of optimum-filtration algorithms: noniterative [4] in the case of constancy of the sought parameters, and iterative [5] when there is no a priori information on the character of the curves being identified.

In identifying local heat-transfer parameters, we are in one sense optimizing a multiple-connected control system when we realize the optimum filtration procedure, i.e., we are taking the most general approach, allowing for the interaction of all of the quantities which determine the behavior of the object being identified.

When heat-utilizing units are being designed, it is necessary to determine the optimum spacing (H) between the cooled tubular elements (Fig. 1). This cannot be done without reliable information on heat-transfer conditions on the inside surfaces of the cooled elements in the gas channel. To obtain such information, it is insufficient to determine the average heat-transfer characteristics. Data on the local coefficients α_1 and α_2 is needed.

Since all of the tubular elements of the unit being examined operate under the same conditions, we will look at part of a cooling jacket within one row of tubes. The temperature was measured at the points indicated in the figure.

The results of temperature measurement for the middle section of the gas channel are shown in Table 1. The problem consists of determining the heat-transfer coefficients, which vary along the boundary but are constant over time. Here, $T_m = 630°C$. The heat-transfer conditions on the side of the cooled surface were as follows: $\alpha_0 = 2 \cdot 10^4$ W/(m²·deg); $T_{m_0} = 170°C$; $\alpha_i = 50$ W/(m²·deg); $T_{m_i} = 20°C$. The thermophysical characteristics of the material: $\lambda = 50$ W/(m²·deg); $c_V = 3.834 \cdot 10^6$ J/(m³·deg).

The results of the identification are also shown in Table 1.

Comparison of the solution of the direct problem with the resulting α_1 and α_2 against the initial data showed that the calculated temperatures differ little from the experimental values (the difference does not exceed 0.5%; not only at points 1, 2, and 3 — used in solving the inverse heat-conduction problem — but at point 4).

In conclusion, we should note that reliable data on heat-transfer conditions make it possible to accurately design the necessary number of cooling elements and to accordingly reduce the metal content of cooling systems.

Local heat-transfer coefficients varying over time were determined by the above approach on the inside surface of a flange on the casing of a K-300-240 high-pressure steam turbine built by the Kharkov Turbine Plant. The thermophysical characteristics of the material of the flange: $\lambda = 56.82 - 0.02 \cdot T$ W/(m·deg); $c_V = 3.494 \cdot 10^6 + 3.375 \cdot 10^3 \cdot T$ J/(m³·deg). We took averaged boundary conditions $\alpha_e = 0.4$ W/(m²·deg), $T_{m_e} = 20°C$ on the external surface of the casing. The measurement error was assumed to have corresponded to a normal distribution of the random variables, while the standard deviation $\sigma = (0.03\text{-}0.05)T_{max}$. The measurements were made at internal points of the flange. We identified values of $\vec{\alpha} = \{\alpha_1, \alpha_2\}$ in the startup regime ($T_m = 0.00745\tau + 200°C$) (Fig. 2a), which covered 6 h. The chosen time interval $\Delta\tau = 10$ min ($\Delta Fo \simeq 0.6$). Figure 2b shows the identified relations α_1 (curve 4) and α_2 (curve 2) and the corresponding standard curves 1 and 3.

To study the stability and convergence of the identification process, the object was placed under unnatural conditions. Here, we chose a standard function $\alpha_2(\tau)$ which did not fully correspond to the actual processes which occur (curve 5), while $\alpha_1(\tau)$ remained as before. In this case, as in the preceding instance, the identification process was stable (curve 6 — approximate relation).

NOTATION

f, nonlinear function; A, B, matrices; X, vector of state; U, control vector; m_X, mathematical expectation of the vector X; $\vec{\alpha}$, vector of the parameters being identified; α, heat-transfer coefficient; T_m, ambient temperature; λ, thermal conductivity; c_V, volumetric specific heat; T, temperature; σ, standard deviation; τ, time; $\Delta\tau$, time interval; ΔFo, dimensionless time interval (increment in the Fourier number).

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