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SOME QUESTIONS INVOLVED IN THE SOLUTION OF INVERSE PROBLEMS IN HEAT CONDUCTION AND AUTOMATED DATA PROCESSING IN THERMOPHYSICAL INVESTIGATIONS

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We consider the problem of constructing systems for the automated processing of thermophysical information and methods for the solution of inverse boundary-value problems in heat conduction.

I. The automation of information processing is today one of the most important methods for increasing the efficiency of scientific investigations and design work. This problem becomes a crucial one in thermophysical investigations closely connected with the production of new specimens of technology, particularly on the thermal design and experimental trials of modern aircraft and their component assemblies.

We can distinguish three main classes of problems in the thermal design of machines and assemblies which clearly require the automation of information processing:

a) the choice of design solutions and the optimization of the parameters of thermally stressed assemblies and systems for maintaining the thermal regime;

b) the choice and identification of mathematical models of the heat-exchange processes being investigated;

c) the processing of the results of experimental investigations and of thermal tests carried out on test stands and under natural conditions.

Although these problems differ from one another, they have important features in common from the viewpoint of formulating and realizing solutions. In the first place, most of them can be stated as extremum problems, and the same numerical optimization methods can be used effectively for their solution. In the second place, all three of these classes of problems are connected with the solution of direct and inverse heat-exchange problems of the same type. In the third place, they are usually nonlinear and require iterative corrections of the solutions as the desired quantities are optimized. As a rule, the problems require a great deal of work, and their solution by digital-computing methods consumes a large amount of machine time.

There are two obvious ways to reduce the amount of time spent on information processing – to devise efficient computation methods and to improve computer hardware. The automating of information-processing systems is a natural combination of these two lines of work. For the purposes of thermophysical research, this means automated systems of thermal design and automated processing of the data of thermal tests. The solution of problems in these two types of systems involves different types of logic, but the algorithmic modules in the software libraries used for them may be the same. The general requirements imposed on the computer hardware (speed of action, memory, service devices) and on the principles of construction of such systems (in particular, requirements imposed with respect to the active integration of the operator with the system) also are roughly the same.

From the foregoing we may draw a preliminary conclusion which is confirmed by a more complete analysis of the question: in many cases it is desirable to construct unified automated systems intended both for processing the data of the thermal experiment and for optimizing the design solutions and parameters of the thermally located assemblies and the thermal protection devices. The algorithm library in such an integrated system will contain general algorithms for solving direct and inverse problems in heat exchange, general procedures for iterative methods of optimization, etc. At the same

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time, the logical schemes for processing information, which consist, in particular, in the choice of specific sequences of algorithms, will, of course, be different.

We referred above to the large amount of work required for solving thermophysical problems on digital computers. Investigators strive to set up a more exact thermal model of the object or process under investigation by taking account of various nonlinearities, of the fact that heat propagation is not one-dimensional, of the transition to a consideration of a more complex region of space variables, and they also strive to solve the problems more precisely, e.g., to use smaller steps in the finite-difference approximation; all of this leads to a sharp and sometimes unacceptably large increase in the amount of computation work. This situation is due to the very principle of operation of digital computers, in which all the variables are discrete and the information is processed sequentially – at any instant of time, only one operation or a limited number of operations can be carried out. Therefore, the total time required for solving a complex thermophysical problem turns out to be very large, and the solution process is much slower than the real physical phenomenon.

A substantial reduction in the amount of machine time used for the processing of thermophysical information can be achieved by hybridizing the computing operations, synthesizing the functions of digital and analog technology [1-6]. From this we can draw the second conclusion that an automated complex oriented toward the processing of thermophysical information should be constructed as a hybrid (analog–digital) system. By including analog modules in a computation process based on the convenient and universal principles of digital programming, we can substantially increase the speed of the system, both because various mathematical operations can be performed in parallel and because it becomes possible to carry out the calculations in real time or even on an accelerated time scale.

The analog modules needed for the calculations can be obtained with the aid of an active analog computer. If high-speed analog computers (with periodization of the solutions) are used, the integration time is reduced to tens of microseconds, which is comparable to the time required for one elementary operation on modern digital computers. It is also important to emphasize that if a sufficiently large amount of equipment is used, the time required for the analog calculations is relatively independent of the magnitude of the problem. The use of this property in combination with the known advantages of digital technology (such as the high accuracy of operation, the high level of automation of the computer, the ample logical possibilities, the capability of long-term memory storage of practically any amount of digital information) makes it possible to construct highly effective computing systems. In such systems the analog and digital parts are combined by means of linkages which include analog–digital and digital–analog converters. The digital computer is used for controlling the analog calculations and calculating the scales, coefficients, initial conditions, and control data.

In [6] we described a hybrid automated system for thermophysical investigations which consists of a two-level multimachine complex made up of general-purpose digital and analog processors.

II. The transition to hybrid computation requires a certain amount of rethinking of calculation methods and the construction of special algorithms for solving direct and inverse heat-exchange problems.

We shall consider the use of a hybrid computing system (HCS) for solving boundary-value inverse heat-conduction problems (IHCP). A preliminary analysis shows that the most desirable method is to hybridize the calculations for the solution of the inverse problems in extremal formulations regularized by A. N. Tikhonov's method and according to the iterative method discussed in [7-11].

Boundary-Value IHCP Regularized by A. N. Tikhonov's Method. In [12] we showed that the regularized formulation of a boundary-value inverse problem with constant coefficients in the heat-conduction equation is equivalent to the algebraic system

$$B(\alpha)\mathbf{u} = \mathbf{D}(\alpha), \tag{1}$$

where $B(\alpha)$, $\mathbf{D}(\alpha)$ – the matrix dependent on the numerical parameter α and the right side of the equation – are obtained by minimizing the finite-dimensional analog of the regularizing functional, and $\mathbf{u}$ is the vector of the desired parameters – time-dependent values of the heat-flux density or the temperature on the boundary of the body. The regularization parameter α, which determines the degree of smoothness of the desired results, is selected by a prescribed rule which harmonizes the precision of the initial data with the discrepancy in temperature.

In the digital realization of the algorithm, the main expenditure of machine time is required for the repeated solution of the system (1) when the values of the parameter α are varied. The machine time increases with the order of the system – the dimension of the reconstructed vector $\mathbf{u}$. The computation time can be shortened and made practically independent of the dimension of $\mathbf{u}$ by using a hybrid computing system. To do this, we used a known method of formulation taking account of the symmetry and positive definiteness of the matrix B. Following this method, we pass to a system of ordinary differential equations

$$\frac{d\mathbf{u}(t)}{dt} + B(\alpha)\,\mathbf{u}(t) = \mathbf{D}(\alpha), \quad t \to \infty, \tag{2}$$

where t is a new independent variable (machine time). The initial condition $\mathbf{u}(0)$ is chosen fairly arbitrarily.

In the limit as $t \to \infty$ the vector function $\mathbf{u}(t)$ will converge to some approximate regularized solution of the inverse problem depending on the given value of α, i.e., problem (2) is equivalent to formulation (1). The time required for reaching the steady state is determined by the chosen value of the accuracy of the entry of the solution into a stationary regime, i.e., a value of ϵ such that $\mathbf{u}(t)$ no longer changes in value.

The integration of differential equations is a typical operation for an active analog computer, and an analog solution of system (2) can be obtained quite rapidly. The functions of information storage and the preparation of information for the following cycle of the analog simulation, corresponding to a different value of α, are performed on the digital computer. It should be noted that when a change is made to another value of α, the scheme of the analog equipment remains the same, and there are likewise no changes in its parameters except for those coefficients which correspond to three or five diagonals of the matrix B, depending on the order of regularization adopted for the problem.

In the same way, we can solve regularized algebraic systems for each spatial layer of the difference network in a numerical algorithm for solving a nonlinear IHCP, which was considered in [13].

Hybrid Calculation of the Coefficients of a Regularized System. The above-described hybrid approach to the determination of an approximate solution of a linear inverse problem assumes that analog computers will be used only for simulating system (2), while the initial data for each analog cycle of calculation are found by a purely digital method. It is possible to construct a hybrid algorithm for solving a given IHCP in which the calculation of the coefficients and the right sides of (2) is carried out by extensive use of the analog part of HCS. We shall show this by using the example of the following problem:

$$\frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial x^2}, \quad 0 < x < b, \quad 0 < \tau \leq \tau_m, \tag{3}$$

$$T(x,\ 0) = 0, \quad T(0,\ \tau) = f(\tau), \quad -\lambda \frac{\partial T(0,\ \tau)}{\partial x} = Q(\tau), \tag{4}$$

$$T(b,\ \tau) = u(\tau),$$

where $f(\tau)$ and $Q(\tau)$ are known functions and $u(\tau)$ is the desired function of the surface temperature of the body.

We shall use one of the variants of the method of straight lines, in which the space coordinate is considered continuous, while the time coordinate consists of a set of discrete points τ_i, i = 1, m, with an equal step $\Delta\tau$. Replacing the time derivative by the relation

$$\left.\frac{\partial T}{\partial \tau}\right|_i \simeq \frac{T_i(x) - T_{i-1}(x)}{\Delta\tau},$$

where $T_i(x) = T(x,\ \tau_i)$, we arrive at the following approximation of the problem (3), (4);

$$\frac{d^2 T_i(x)}{dx^2} - \frac{1}{a\Delta\tau} T_i(x) = \frac{-1}{a\Delta\tau} T_{i-1}(x), \quad 0 < x < b, \quad i = \overline{1,\ m}, \tag{5}$$

$$T_0(x) = 0, \quad T_i(0) = f_i, \quad \frac{dT_i(0)}{dx} = \varphi_i \equiv -\frac{Q_i}{\lambda},$$

$$T_i(b) = u_i - ?, \quad i = \overline{1,\ m}.$$

We must determine the quantities u_n, n = 1, 2, ..., m, from the condition that we must have a minimum of the regularized discrepancy

$$\Phi[\mathbf{u}] = \sum_{i=1}^{m} [T_i(0) - f_i]^2 + \alpha \sum_{i=1}^{m} (u_i - u_{i-1})^2,$$

where the temperatures $T_i(0)$ are obtained from the solution of system (5) for the given vectors of the boundary conditions – the known vector $\varphi = [\varphi_1, \varphi_2, ..., \varphi_m]^T$ and the variable vector $\mathbf{u} = [u_1, u_2, ..., u_m]^T$.

Setting the derivatives $\partial\Phi/\partial u_n$ equal to 0, we write the necessary extremum conditions in the form

$$\sum_{i=n}^{m} [T_i(0) - f_i] \frac{\partial T_i(0)}{\partial u_n} + \alpha(-u_{n-1} + 2u_n - u_{n+1}) = 0, \quad n = \overline{1,m}. \tag{6}$$

In order to find the partial derivatives $\partial T_i(0)/\partial u_n$ (the sensitivity coefficients), we proceed as follows. We differentiate the right and left sides of Eq. (5) with respect to u_n and interchange the order of differentiation with respect to x and u_n. Introducing the notation $\psi_{in}(x) = \partial T_i(x)/\partial u_n$, we obtain

$$\frac{d^2\psi_{in}(x)}{dx^2} - \frac{1}{a\Delta\tau}\psi_{in}(x) = -\frac{1}{a\Delta\tau}\psi_{i-1,n}(x). \tag{7}$$

The solution of (7) must satisfy the boundary conditions

$$\frac{d\psi_{in}(0)}{dx} = 0, \quad \psi_{in}(b) = \begin{cases} 1, & i = n \\ 0, & i \neq n, \end{cases} \tag{8}$$

$$n = \overline{1, m}, \quad i = \overline{n, m}.$$

It is not difficult to see that

$$\psi_{11} = \psi_{22} = \ldots = \psi_{mm},$$

$$\psi_{21} = \psi_{32} = \ldots = \psi_{m,m-1},$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\psi_{i1} = \psi_{i+1,2} = \ldots \psi_{i+j,j+1} = \ldots = \psi_{m,m-i+1}.$$

Thus, to determine all the derivatives $\psi_{in}(0) = \partial T_i(0)/\partial u_n$, we must solve the two-point boundary-value problem (7), (8) only m times – for n = 1, i = 1, 2, ..., m. It is natural to use the analog part of the hybrid computing system for this purpose. Let us consider this question in more detail.

Problem (7), (8) is a linear boundary-value formulation in which we are trying to find the solution of a system of differential equations in some interval on the basis of the conditions determining the connection between the values of the solution and its derivatives at the endpoints of the interval. One of the effective methods for finding this solution, which enables us to overcome the difficulties associated with the existence of an unstable integration regime on the analog computer for small values of $\Delta\tau$, is the reduction of this formulation to a problem with initial conditions by the factorization method.

We introduce the notation $y(x) = \psi_{in}(x)$, $g = \frac{1}{a\Delta\tau}$, $h(x) = -\frac{1}{a\Delta\tau}\psi_{i-1,n}(x)$ and rewrite the boundary-value problem (7), (8):

$$L(y) \equiv y'' - gy = h, \quad x \in (0, b), \tag{9}$$

$$y'(0) = 0, \tag{10}$$

$$y(b) = c, \tag{11}$$

where c = 0 or 1, depending on the relation between the numbers i and n.

To solve the problem (8)-(11), we use one of the factorization methods indicated in [14]. We construct the sequence of functions u_k and v_k, k = 1, 2, ... , setting $v_0 = 0$ and using the differential equations

$$\frac{dv_k}{dx} + \sqrt{g}\, v_k = \frac{h}{2\sqrt{g}}, \tag{12}$$

$$\frac{dw_k}{dx} - \sqrt{g}\, w_k = \frac{h}{2\sqrt{g}} \tag{13}$$

with the initial conditions

$$\frac{dv_k(0)}{dx} = \frac{dw_{k-1}(0)}{dx}, \quad w_k(b) = c + v_k(b).$$

The function $y_k = w_k - v_k$, as can readily be verified, satisfies Eq. (9) and the condition (11). Furthermore, it was shown in [14] that as $k \to \infty$, the sequence y_k converges to the solution of the boundary-value problem (9)-(11). The rate of convergence of this iterative process is high (the desired accuracy is achieved after several iterations), and it increases with the length of the interval [0, b].

In carrying out this process, we do not encounter any problems, provided that we maintain the stability of the calculation.

If we introduce a new independent variable x' = b – x, then (13) is transformed into the equation

$$\frac{dw_k(x')}{dx'} - \sqrt{g}\, w_k(x') = \frac{h(x')}{2\sqrt{g}}. \tag{14}$$

with the initial condition

$$w_k|_{x'=0} = c + v_k|_{x'=0}.$$

As a result, Eq. (14) is integrated in the same direction as (12) – from left to right. These operations are assigned to the analog computer when the hybrid algorithm is set up.

It should be noted that a stable analog solution of the initial equation (9) can also be carried out by using a somewhat different variant of the factorization method, known as the decomposition method [15].

In order to solve system (6) for u_n, n = 1, 2, ..., m, it is necessary, in addition to the sensitivity coefficients $\psi_{in}(0)$, to find the connection of the quantities $T_i|_{x=0}$ with the desired values of u_n. It is not difficult to show that we finally obtain the following formulation for the regularized algebraic system:

$$\sum_{l=1}^{m} u_l P_{ln} + \alpha(-u_{n-1} + 2u_n - u_{n+1}) = b_n, \quad n = \overline{1, m}, \tag{15}$$

where

$$P_{ln} = \sum_{k=l}^{m} \psi_{kl}(0)\,\psi_{kn}(0), \qquad b_n = \sum_{i=n}^{m} \psi_{in}(0) f_i.$$

To Eq. (15) we must add two conditions determining the values u_0 and u_{m+1}, e.g., from the approximation of the derivative du/dx at the points $\tau = 0$, τ_m [12].

We calculate the sums in the determination of the coefficients P_{ln} and b_n and also "remember" the resulting values by using the digital computer. The solution of the regularized algebraic system for different values of the parameter α can be carried out by means of the hybrid computer using the convergence method.

Remark I. In the above discussion, we considered the boundary temperature as the desired function; however, the algorithms given can be carried over practically completely to the case of reconstructing the heat flux density $q(\tau_n) = -\lambda(dT_n(b)/dx)$.

Remark II. Without any theoretical difficulties, we can extend the proposed hybrid method of solving IHCP to a heat-conduction equation with a convective term and distributed heat sources, including the case when the coefficients and the source are functions of the coordinate x. In these cases the number of sensitivity coefficients can also be reduced from m(m + 1)/2 to m. The solution of the resulting m boundary-value problems for determining the sensitivity coefficients is carried out on the HCS according to the scheme described above.

In the case when the coefficients and the source depend not only on x but on τ, we must calculate m(m + 1)/2 sensitivity coefficients.

Solution of Inverse Problems by Iterative Methods. On the basis of iterative gradient methods for minimizing the temperature discrepancy, we have worked out efficient algorithms for solving linear and nonlinear IHCP [7-10]. It is easy to construct iterative processes which yield an approximation to the desired function not only as an average but also taking account of the necessary degree of smoothness of the solution [9, 10].

The parts of the iterative algorithms which are most difficult to set up for digital calculation are the procedures for solving boundary-value problems for the heat-conduction equation which determine the temperature in the body and the temperature increments, as well as the procedure for finding the discrepancy gradient by solving the conjugate boundary-value problem. Therefore, the speed of the iterative algorithms may be considerably increased if the functions of integrating these boundary-value problems are assigned to the analog part of the HCS.

Rules for Halting the Iteration for Gradient Methods of Minimization. The results of the solution of various inverse problems in heat conduction show that iterative processes of the steepest-descent type and the conjugate-gradients type are stable with respect to approximation errors and errors connected with the computer mechanization of the algorithms. This conclusion is obtained both for the use of digital computers and for the use of HCS. Beginning with a poor initial approximation, these iterative processes converge rapidly at first, and afterwards (after four to seven iterations) they become much slower. In most cases it is possible to find the shape of the desired function, which changes little thereafter. This behavior of the approximations makes it possible to conduct a search for the necessary element on the basis of the condition that the iterative process converges if the input data are unperturbed or are subjected to preliminary smoothing.

However, if the initial data include fluctuation errors, the behavior of the iterative process constructed by the steepest-descent or conjugate-gradients method can be tentatively subdivided into stages: the finding and correction of the main structural features of the desired function followed by the gradual development of oscillations in the solution. In this case the time when the process should be stopped can be determined by the discrepancy criterion, i.e., we must introduce an admissible level of minimization of the target functional and harmonize the number of iterations with the accuracy of the

specification of the initial data, in order to stop the process somewhere at the junction of the first and second stages. For linear formulations of the problem, this approach may be justified by rigorous arguments (see [11]).

It should be noted that a sufficiently accurate determination of the admissible level of minimization of the discrepancy is not always possible. In this situation we may resort to two other empirical methods for halting the iteration process which do not require a knowledge of the value of the error in the initial data. To use them, we must know (at least) two independent random realizations of the measured temperature $T_1^*(\tau)$ and $T_2^*(\tau)$ at some point inside the body, and, as a rule, the inverse problem is additionally defined by specifying at some other point of the body a supplementary condition concerning the temperature or the heat-flux density.

Method I. We construct two iteration sequences for the desired value, $u_1^k(\tau)=u^k(\tau)|_{T_1^*}$ and $u_2^k(\tau)=u^k(\tau)|_{T_2^*}$, for two known temperature realizations, respectively. In these sequences we take different initial approximations $u_1^0(\tau)$ and $u_2^0(\tau)$. Among the elements $u_1^k(\tau)$ and $u_2^k(\tau)$ we try to find the functions $u_1^r(\tau)$ and $u_r^l(\tau)$ which are closest to each other in the sense of minimizing the quantity $\|u_1-u_2\|$. One of these functions (or the result obtained by averaging them at each instant of time) is taken as the required approximation to the desired solution. Analysis of the calculations has shown that when we choose initial estimates which are far from each other, this method yields entirely acceptable results, which are close to the results of the solution of the IHCP obtained in accordance with the iterative discrepancy method.

Method II. The method proposed in [16] for choosing the regularization parameter in A. N. Tikhonov's method can be extended to the iterative algorithms. In this case we construct an iterative sequence $\{u_1^k(\tau)\}$ with input data in the form of one of the random realizations of the temperature, e.g., $T_1^*(\tau)$. The necessary number of iterations is determined from the condition that the temperature $T_1^k(\tau)$, calculated for $u_1^k(\tau)$, must be as close as possible to the other input function $T_2^*(\tau)$:

$$r: \|T_1^r - T_2^*\| = \min_k \|T_1^k - T_2^*\|.$$

We can thus find $u_2^l(\tau)$ by "fitting" $T_2^k(\tau)$ to the realization $T_1^*(\tau)$ and then average the resulting functions u_1^r and u_2^l. In the solution of the methodological examples, method II yielded approximately the same results as method I.

Remark. From the practical viewpoint the two random realizations of the temperature $T_1^*(\tau)$ and $T_2^*(\tau)$ can be obtained by means of two different temperature sensors. In the case of a single experimental curve $T^*(\tau)$, we select two time series, $\{T_{1i}^*\}$ and $\{T_{2i}^*\}$, from it. To do this, we use different steps for the discretization of the continuous measurement process, as well as a "shift" of the time networks of temperature recording. In both cases we must, on the one hand, avoid correlated data (since the useful signal is usually burdened with nonwhite noise) and, on the other hand, avoid the effect of masking the frequencies of the useful signal.

In the foregoing discussion we have considered some aspects of the hybrid solution of boundary-value IHCP. It is also possible to construct effective hybrid methods for solving other types of inverse problems, specifically inverse problems in heat exchange in technological systems, used for identifying the parameters of thermal models of these systems. By using HCS, we can also reduce considerably the amount of time consumed in solving direct heat-conduction problems connected with the calculations of temperature fields in structures and heat-shielding coverings, which may be particularly effective in the choice and optimization of the parameters of a technological system being designed, when such problems must be solved repeatedly.

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AUTOMATION OF THE PRIMARY PROCESSING OF DATA OF A THERMAL EXPERIMENT

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The problems involved in automating the processing of experimental data are considered. Primary-processing algorithms based on methods of analyzing nonstationary random processes are described.

Considerable attention is being given at present to designing automated data-processing systems for thermal experiments. The need to construct such systems is obvious. Automated data-processing systems enable one to eliminate manual operation, which to a large extent affects the operational capability and accuracy with which the results can be processed. Until recently "stationary" experiments under steady-state heat-exchange conditions have largely been carried out when studying thermophysical processes. This approach has simplified the theoretical methods by which the experimental data is processed. The amount of computational work involved was, as a rule, small. Incidental computer calculations to a large extent met the requirements of the investigations. The need to solve more detailed and more complex experimental problems when studying different nonstationary thermal regimes [1] has necessitated the development of more complex methods, which considerably increase the complexity and the amount of processing work involved. Manual or incidental computer calculations now are not only not sensible but in many cases are generally impracticable. Hence, an automated data-processing system for thermal experiments should improve the quality, increase the accuracy and information content of the investigations as a result of a more complete and fundamental analysis of the measurement results, increase the operational capability of the experimental data processing, intensify the research, and reduce the cost of typical multiple experiments and tests. In addition, an automated data-processing system widens the possibility of rational planning of a thermal experiment, enables the processing and analysis of the data to be flexibly organized, and enables one to correct and simultaneously process and store large amounts of data. An important feature also is that an automated system eliminates any subjective approach when decoding experimental data and when estimating the characteristics obtained.

The presence in a thermal experiment of a large number of unconnected factors which affect the physical processes being investigated, and distortion of the useful data by the recording apparatus lead to the need for careful analysis of the results obtained. Consequently, it is necessary to organize the automated processing procedure in such a way as to reduce the loss of useful information to a minimum.

We propose the following principles for constructing the software of an automated data-processing system. Processing is divided into three stages: preparation of the experimental data, and primary and secondary processing. The preparation involves a specific apparatus part of the automated data-processing system, and at the end of the first stage matrices of the initial data are formulated in a form convenient for introduction into the computer of the automated data-processing system. Primary processing involves a statistical analysis of the experimental data [2, 3], while secondary processing involves solving the main applied problems.

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