A METHOD OF RAPID IDENTIFICATION OF HEAT FLUXES

O. M. Alifanov and I. Yu. Gedzhadze

In design, development, and operation of crucial engineering systems subjected to high heat fluxes, it is often necessary to observe the thermal state of the object in real time. The authors suggest an approach that is based on the methodology of solution of inverse heat-conduction problems (IHCP) and is a special adaptation of these methods for solution of observation problems. The approach is based on the idea of the possibility of identifying the current thermal state of the object with the use of measurements that are chronologically close to the current time, which leads to formulation of the retrospective boundary-value IHCP in a local time interval. A solution to this problem is considered, and results and estimates of the accuracy of simulation are presented.

Introduction. The functioning of many modern engineering systems is accompanied by high-intensity heat transfer processes that can be caused by interaction with the environment and by operation of power plants. Therefore, optimization of heat regimes is an important component of systems subjected to high heat fluxes. The most general trends consist in simulation of heat transfer processes in members of the structure subjected to high heat fluxes with subsequent choice of their operating characteristics so that their serviceability be ensured with a certain safety factor. However, situations are quite possible in which such an approach leads to the choice of nonoptimum designs. This can be explained by the complexity of processes considered and, as a result, by incomplete adequacy of the mathematical models that are used for their description and by the effect of various random factors an account of which is often absolutely impossible. In particular, the matter of optimality becomes especially important in development of reusable space systems and long-service apparatus, in which excess of the safety factor has an important effect on the final efficiency and cost. Therefore, in some cases it would be reasonable to use intelligent heat systems, i.e., systems in which control by feedback could be implemented, which is fully consistent with advanced trends in technology.

We can give some examples of various versions of active thermal-protection systems such as convective, film, and porous cooling of structures under high heat fluxes. In these systems, the pumping intensity of the heat-transfer agent or the mass flow rate of the coolant can be used as the controlling parameter, and the heat flux into the heated wall or its temperature, as the controlled one. Simultaneously, these quantities are observed characteristics. In most cases direct measurement of heat fluxes or temperatures of heated surfaces is difficult; however, one can obtain results by solving the corresponding IHCP on the basis of readings of thermal sensors that are mounted inside the wall or on its internal boundary. It is evident that such adaptive systems could allow optimization of the power of the coolant pumping systems or the coolant flow rate.

Thermal experiments and tests are another area where control of heat fluxes based on the servo principle or continuous diagnostics of the temperatures of the objects may be required. In the first case, it is necessary to reproduce specified time dependences of heat fluxes or temperatures in specimens or models on the basis of information obtained from control sensors, while in the second case it is necessary to process experimental data immediately in order to determine the time of emergency stop of the tests to avoid damage to expensive equipment.

To develop thermal systems in which control by feedback is performed, it is necessary first of all to solve the problem of observation of the thermal state of the object in real time. (The thermal state is as the temperature...
distribution over the coordinates and the conditions of heat transfer at the boundaries of the object.) In this case use of the methodology of the IHCP brings about important new capabilities. However, two problems are involved here. The first is associated with the physical nature of the heat-conduction process and is expressed in delay of the response to the unknown action and its substantial damping. On the one hand, this is a physical reason for the incorrectness of the IHCP and all resultant mathematical properties. On the other (which is also very important in the present case), any estimate of the current thermal state of the object is only an extrapolation. As is shown by calculations, the extrapolation error can be admissible high and estimates of reasonable accuracy can be obtained only retrospectively.

The second problem is construction of algorithms that are adapted in a special way to rapid solution of the IHCP. In this case it is desirable that the time of solution of the problem be a small part of the interval of the forced retrospective shift. The combination of fast algorithms with the capabilities of modern special computers based on of the third generation of signal processors inspires hope for a successful solution to this problem.

Successive algorithms in which a limited sample is used for estimation of the current thermal state of the object are the most suitable for solution of the IHCP in real (or close to real) time. In considering the available methods, it is necessary first of all to pay attention to the method of construction of the the successive procedure and the means of inclusion of the nonlinearity and incorrectness of the problem. The following methods can be used here: direct numerical methods based on the finite-difference representation of the heat-conduction equation [1-3], the method of optimum dynamic filtration [4], and methods of successive functional approximation [2]. All these methods have some drawbacks, among which the most important is that these algorithms are constructed so that a subsequent estimate of the thermal state of the object is computed on the basis of the previous one. First, this means that it is necessary either to have an estimate of the thermal state of the object at some time, which is assumed to be the initial time, or to develop the transient regime and be sure that the estimation process converges. In practice, this necessitates, for example, inclusion of algorithms before the start of the thermal process and their subsequent continuous operation. Second, with this method of solution, computational errors in the current time cross section are transferred to the subsequent ones and it cannot be excluded that under certain conditions they will accumulate.

In what follows, a method is suggested for construction of successive algorithms that is based on consideration of the studied thermal process within a certain local interval that precedes the current time. In this case, along with the boundary condition, the initial temperature distribution is also unknown. In this sense, according to the classification of [1], this formulation of the IHCP can be classified as a retrospective boundary-value problem. This formulation is sustainable in the sense that for solution of the problem, no initial information about the previous states is required (although if this information is available, it can be used). Successive repetition of this procedure with a chosen time step allows recovery of the thermal state of the object in a time segment of arbitrary length. Since estimation events in successive local intervals are independent, in principle the length of the time shift between them can be any value, in particular, longer than the interval itself, and it is determined by the expenditure on estimation in the local interval. In other words, in any case, estimates of the thermal state of the object can be obtained, and it is only necessary to determine what the value of the time step is and whether the latter is sufficient for subsequent control.

We consider the inverse problem for the quasilinear heat-conduction equation (the coefficients of the equation depend on the temperature). However, in the first part we investigate the solution of the retrospective boundary-value IHCP for the linear heat-conduction equation with constant coefficients, for which we obtain a regularized inverse operator that depends explicitly on the regularization parameter. In doing this, to choose optimum values for the local interval, the retrospective shift, and the step between measurements, use will be made of an approach based on analysis of the accuracy of the solution. In the second part, we consider the solution of the IHCP for the quasilinear equation. In essence, we use a regularized variant of the method of successive approximations in which in each iteration a linear IHCP that will be considered in detail later is solved. The conditions for conversion of this iteration process are analyzed. A method for choosing the regularization parameter that would ensure the most rapid convergence and a stopping rule are suggested. Accuracy estimates are presented.