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A method for transient thermal load estimation and its application to identification of aerodynamic heating on atmospheric reentry capsule

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ABSTRACT

The purpose of this work is to formulate a simple method which can be used for the transient thermal load identification. The proposed algorithm can reconstruct the transient temperature distribution in a whole component based on measured temperatures in selected points on the component surface. The presented method may use some commercial heat transfer modelling software. In this work, ANSYS Multiphysics is applied. Two numerical examples of identification of the transient thermal load taken from literature are presented. The determination of the heating process of a simple two-dimensional plate and the recognition of the aerodynamic heating on the atmospheric reentry capsule will demonstrate high accuracy and stability of the proposed algorithm. Future time steps and smoothing filters are used to stabilize the solution of an ill-posed problem. The presented method is easy to use for engineers working in the aerospace or power industry.

1. Introduction

The thermal analysis plays a significant role in the design of components subjected to high temperatures and intended for many engineering fields such as the aerospace or power industries. One of the major difficulties in carrying out the thermal analysis is the definition of all boundary conditions. The boundary condition formulation is not easy due to many factors, e.g. the irregular geometry of the component edge or the trouble in interpreting the physical phenomena occurring on the surface in time and space.

An interesting method of solving this difficulty is to include additional temperature measurements instead of unknown boundary conditions and then formulate a transient inverse heat conduction problem (IHCP).

For elements with simple and regular shapes, assuming that the material thermal and physical properties are constant, exact methods of solving the 1-D inverse heat conduction problem may be used [1–3]. Solving multidimensional inverse problems related to bodies with temperature-dependent physical properties requires numerical methods. The methods of solving steady- and transient-state two-dimensional inverse problems of heat conduction in solid bodies with simple shapes are presented in [4] and [5–7], respectively. The algorithms used for inverse problems in three dimensions are presented in [8,9] and a general method for solving multidimensional inverse heat conduction is shown in [10]. There are very few works presenting the solution of multidimensional inverse heat conduction in solid bodies with complex shapes. An attempt is made in [11] to use the method [12] to identify the unknown heat flux on the surface of a reentry capsule with a complex shape, but the number of necessary temperature measurements is very high and difficult to carry out in practice.

Inverse methods may be also used for optimization of the power unit start-up and shut-down operations, which may lead to the heat loss reduction during these operations and extend the power unit life span [13,14].

The IHCP solution often includes a complex mathematical model [1–14] and therefore it is difficult to perform for many engineers. Commercial heat transfer modelling software is hard to apply because this requires that all boundary conditions should be defined.

The purpose of this work is to propose a simple inverse method which can be used for the transient thermal load estimation on solid bodies with complex shapes.

The biggest advantage of the proposed method in comparison with the existing ones is its simplicity. This original new formulation does not include a sophisticated mathematical model and may use some commercial heat transfer modelling software. In this work, ANSYS Multiphysics software [16] that utilizes the finite element method (FEM) is applied. Another advantage is the generality of the proposed formulation. This algorithm will be applied to identify aerodynamic heating on the atmospheric reentry capsule, but it may also be used for many other transient phenomena if they have a direct solution only. The method may be used to solve multidimensional inverse problems in bodies with simple and complex geometries. It makes it possible to take account

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of different nonlinearities, such as temperature-dependent material properties or nonlinear boundary conditions, and this paper presents radiation-related nonlinearity as well.

In this work, future time steps [15] and smoothing filters [14] are used to stabilize the ill-posed problem solution. Two numerical examples of identification of the transient thermal load taken from [11] will be presented. The determination of the heating process of a simple two-dimensional plate and the recognition of the aerodynamic heating on the atmospheric reentry capsule will demonstrate high accuracy and stability of the proposed algorithm. The results obtained by the proposed method and the method presented in [11] will be compared.

2. Formulation of the method

The equation governing the transient heat conduction in solids is expressed as follows:

$$c(T)\rho(T)\frac{\partial T}{\partial t} = -\nabla \cdot \boldsymbol{q}, \tag{1}$$

where $\mathbf{q}$ is the heat flux vector defined by Fourier's law

$$\boldsymbol{q} = -\boldsymbol{D}\nabla T. \tag{2}$$

$\mathbf{D}$ is the conductivity matrix

$$\boldsymbol{D} = \begin{bmatrix} k_x(T) & 0 & 0 \\ 0 & k_y(T) & 0 \\ 0 & 0 & k_z(T) \end{bmatrix} \tag{3}$$

If the material is isotropic, then $k_x(T) = k_y(T) = k_z(T) = k(T)$. All the material properties: c – specific heat, k – thermal conductivity, ρ – density can be considered as known temperature or temperature-independent functions.

Transient heat conduction problems are initial-boundary problems and appropriate initial and boundary conditions have to be defined. The initial condition is the temperature of a body at its first moment $t_0 = 0$ s.

$$T(\boldsymbol{r}, t)|_{t_0=0} = T_0(\boldsymbol{r}) \tag{4}$$

where $\mathbf{r}$ is the position vector.

Typically, three boundary conditions – of the 1st, 2nd and 3rd kind – may be assigned to the body boundary

$$T|_{\Gamma_T} = T_b \tag{5}$$

$$(\boldsymbol{D}\nabla T \cdot \boldsymbol{n})|_{\Gamma_q} = q_B \tag{6}$$

$$(\boldsymbol{D}\nabla T \cdot \boldsymbol{n})|_{\Gamma_h} = h(T_m - T|_{\Gamma_h}) \tag{7}$$

where

- $\mathbf{n}$ – unit outward normal vector to boundary Γ,
- T_b – temperature set on the body boundary Γ_T,
- q_B – heat flux set on the body boundary Γ_q,
- h – heat transfer coefficient set on the body boundary Γ_h,
- T_m – temperature of the medium.

If a body surface is cooled or heated by radiation, then the boundary condition is nonlinear

$$(\boldsymbol{D}\nabla T \cdot \boldsymbol{n})|_{\Gamma_r} = \sigma F\left[T_r^4 - (T|_{\Gamma_r})^4\right] \tag{8}$$

where σ is a Stefan–Boltzmann constant, T_r is the surrounding temperature and F is a shape coefficient which takes account of the surface emissivity and the mutual configuration function.

A phenomenon described by equations (1)–(8), in which boundary conditions are specified over the entire boundary, is referred to as a direct transient heat conduction problem (Fig. 1).

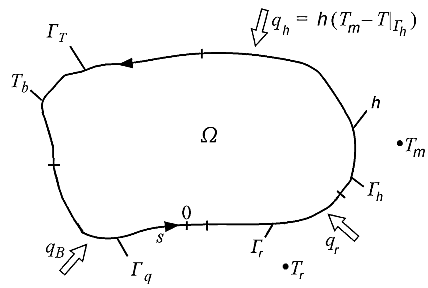

Fig. 1. A direct transient heat conduction problem.

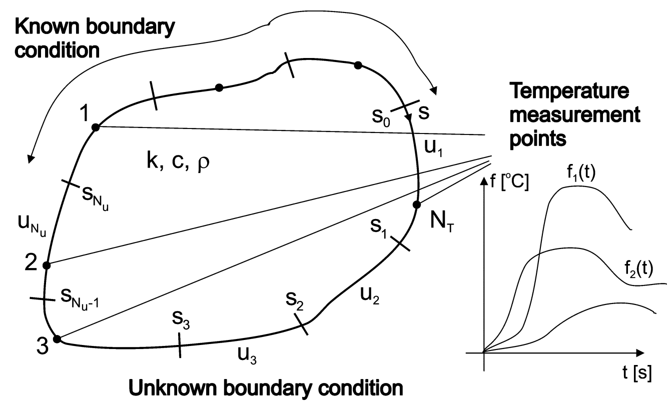

Fig. 2. An inverse problem with known and unknown boundary conditions, and additional temperature measurement points.

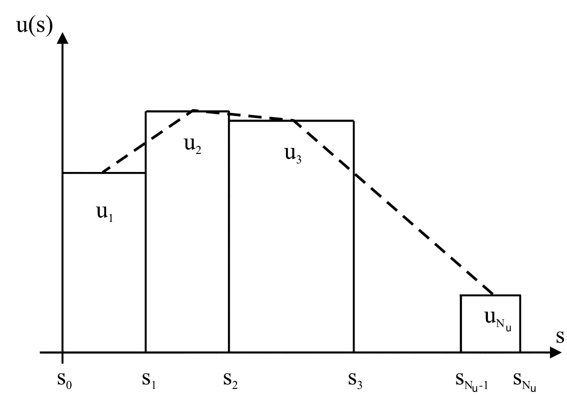

Fig. 3. Staircase or piecewise linear function of an unknown heat flux on the body surface.

If boundary conditions (5)–(8) are unknown on parts of the domain boundary, the problem becomes ill-posed and additional interior temperature measurements are needed in the analysis (Fig. 2)

$$f_i(t) = T(\boldsymbol{r}_i) \quad i = 1, \ldots, N_T \tag{9}$$

The first step of the proposed method is the discretization of any unknown boundary condition type into N_u intervals and its approximation by the 2nd kind boundary condition (6). It may be assumed as a staircase or a piecewise linear function on the body surface (Fig. 3).

The aim is to choose such $\boldsymbol{u}(u_1(t), u_2(t), \ldots, u_{N_u}(t))$ in time that the computed temperatures should agree within certain limits with the temperature values measured experimentally. It may be expressed as

$$T_i(\boldsymbol{u}, \boldsymbol{r}_i, t) - f_i(t) \cong 0, \quad i = 1, \ldots, N_T \tag{10}$$