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DAMAGE IDENTIFICATION IN STRUCTURES BY MEANS OF THERMOGRAPHIC METHODS

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Summary The detection of cracks, inclusions or voids as well as their location, orientation and size is performed using measurements of surface temperature caused by steady state or transient thermal loading. On the basis of measurement results, an inverse steady state or transient heat transfer problem is formulated and next solved. The inverse solution is constructed by minimizing the properly defined distance norm of measured and model temperatures. In this stage of research the real measurements are numerically simulated. The model temperature distribution is calculated using the finite element model of a structure, while in minimizing of distance norm functional the gradient-oriented methods are used. The proper sensitivities of introduced identification functional are derived. For particular domain transformation these sensitivities are calculated using a class of path-independent sensitivity integrals. Some numerical examples are presented in order to justify the presented approach.

INTRODUCTION

The prediction of location and degree of damage in existing engineering structures is of great importance from the point of view of their serviceability and safety. Visual inspection and extensive testing can be employed to locate and measure the degradation of structure by a wide class of non-destructive techniques. In the present paper, we shall study damage or fault detection by the analysis of transient of steady state thermal response of structures. The detection of surface, subsurface or internal cracks, inclusions or voids as well as their location, orientation and size can be performed using infrared measurements of surface temperature caused by applied thermal loading. In order to increase the number of available measurement data, the thermal multi-loading case is considered.. The inverse solution is constructed by minimizing the properly defined distance norm of measured and model temperatures at specified surface points or along specified surface lines. In this stage of research the infrared measurements will be numerically simulated. To make the simulation more realistic, some random error will be introduced into simulated measurements in order to model the unavoidable tolerance of real measurement. The influence of magnitude of this error on accuracy of defect estimation will also be inspected.

PROBLEM FORMULATION

Let us consider a transient heat transfer problem within non-homogeneous two-dimensional domain, Fig. 1, described by the conduction equation supplemented with proper set of boundary and initial conditions. The defect in a structure is modeled by introducing two subdomains Ω_1 and Ω_2, so that $\Omega=\Omega_1\cup\Omega_2$ and Ω_1 is a structure domain with conductivity matrix $\mathbf{A}_1$ while subdomain Ω_2 with conductivity matrix $\mathbf{A}_2$ models the crack, inclusion or void within structure domain. The detailed analysis associated with shape modification and optimal design for problem described by Eq.(1) was performed in [3], whereas the steady state problem was discussed in [2]. In this paper the identification problem associated with structural shape will be considered. To identify the structural shape (within the assumed in advance shape class) or location of defect, the identification functional in the form of proper distance norm between temperature fields within the model and real structure should be introduced. In particular, the size, position and orientation of defect can be identified using this procedure. In general, the identification functional can be assumed in the form of time and space integral, given in the form:

$$I(T,T^r,\mathbf{b},t)=\int_{t_0}^{t_f}\int_{\Gamma(\mathbf{b})}\Phi[T(t_k),T^r(t_k)]d\Gamma_r dt \; = \; I(T,T^r,\mathbf{b},t)=\sum_{k=1}^{n}\xi_k\int_{\Gamma(\mathbf{b})}\Phi[T(t_k),T^r(t_k)]d\Gamma_r \qquad (1)$$

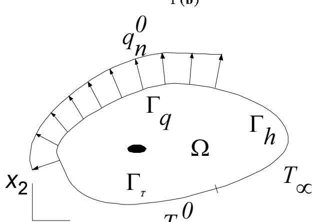

Figure 1: 2D body with internal defect.

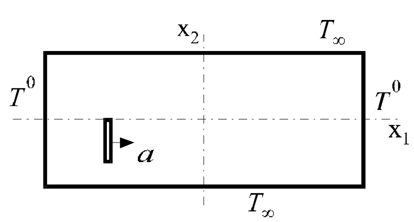

Figure 2: Rectangular disk with translated internal hole

where Φ is an arbitrary function depending on the predicted and measured temperatures T and T^r within assumed time period (t_0, t_f) and Γ_r denotes the boundary portion on which the measurement is performed. The parameters $\mathbf{b}$ specify the defect properties, and in particular they can specify the position, orientation and scale change of identified defect. Thus, we use the time window of bandwidth $t_f - t_0$ in order to gather the experimental data required to identification procedure.

Both the initial and final times t_0 and t_f of identification procedure can be different from the initial and final times of transient heat transfer problem. Instead of time integral, also the summation of space integral over Γ_r at some selected time instant t_k can be used in formulation of the identification norm, as shown in expression (1). In this case, the summation is expanded on assumed number of time instances and ξ_k denote some weighting factors. Let us note that both expressions in (1) are equivalent, when the Gauss quadrature method is used in numerical integration of time integral in (1). Two particular forms of functional (1) can be considered, namely:

$$I(T,T^r,t,\mathbf{b}) = \int_0^{t_f} \sqrt{\int_{\Gamma_m} \alpha(\mathbf{x})[T(\mathbf{x},t_k,\mathbf{b}) - T^r(\mathbf{x},t_k)]^2 d\Gamma_r}\, dt = \sum_{k=1}^{n} \xi_k \sqrt{\int_{\Gamma_m} \alpha(\mathbf{x})[T(\mathbf{x},t_k,\mathbf{b}) - T^r(\mathbf{x},t_k)]^2 d\Gamma_r} \tag{2}$$

where $\alpha(\mathbf{x})$ is a weighting function, which can magnify or weaken the difference between the model and measured temperature on some portion of structural boundary. The other form of identification functional can be also used, basing on measurement of temperature differences for structure or its model at initial and actual conditions.

The identification problem can be now formulated as follows

$$\text{min. } I(T,\, t,\, \mathbf{b}) \text{ subjected to equality constraints describing heat transfer problem} \tag{3}$$

Since in minimizing of the assumed form of identification functional the gradient-oriented methods will be used, thus there will be a need to calculate the proper sensitivities of introduced identification functional. This procedure will be performed using the adjoint approach to sensitivity analysis.

PATH-INDEPENDENT SENSITIVITY ANALYSIS

In performing the calculations of sensitivity expressions of identification functional (1) the general adjoint or direct method approaches can be used. For particular case of sensitivity analysis with respect to translation and rotation of defect a class of path-independent sensitivity integrals derived by Dems and Mroz [1,4] will be used. This class of sensitivity integrals will allow for integration of desired sensitivity expressions along paths situated far from singular points or areas of rapid changes of temperature gradient. The sensitivity analysis of identification problem will be performed using the material derivative concept and adjoint approach. The application of path independent sensitivity integrals will also require the specification of primary and adjoint fields depending on the form of applied identification functional, as well as the closed contours containing inside the analyzed defect.

In deriving the sensitivity expressions, both the transient and steady state heat transfer cases are considered. In this last case we omit the time dependence of state fields of heat transfer problem as well as in identification functional (1). Therefore, the obtained path-independent sensitivity expressions are also time independent.

The method presented in the paper can be also extended to the case of other physical field (i.e. electric, magnetic) described by the harmonic equation.

EXAMPLES

In order to justify the presented approach, the identification of location of rectangular hole in disk shown in Fig. 2 was performed using the steady state thermal loading. The internal hole within a model disk domain was allowed to translate along x_1 axis in order to identify its location in real structure. The prescribed temperature was applied along boundaries x_1 = const. and convection conditions were assumed along boundary portions x_2 = const. The measured temperature along boundaries x_2 = const. was numerically simulated and some random error of magnitude 1% and 2% was introduced into simulation. In the case of error free identification the location of hole along x_1 direction was exact, while introducing the random error of magnitude 1% and 2% respectively, results in error of location identification equal to 1.09% and 1.54%, respectively.

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