A Review on Solution of Inverse Heat Conduction Problems

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Abstract - A method to solve inverse heat conduction problem (IHCP) is to determine surface heat flux or boundary temperature from the measurement of temperature in the interior of the solid. The method proves to be applicable where a direct measurement of surface heat flux or boundary temperature is difficult, regarding to several working condition. The literature reviewed here discuss about one dimensional inverse heat conduction problem. Methods, phenomena, and important outcomes of other investigation are briefly discussed.

I. INTRODUCTION

The heat conduction problem is used to determine the surface heat flux and temperature distribution in the body from transient measured temperature history at one or more interior points. The problem that occurs generally is in instrumentation systems. Distinctive instances involves the monitoring of thermal stress in thick-walled pressure parts of power plants based on temperature measurements at the element external to the surface, and predictions of heat flux and temperature from calorimeter type instrumentation. Changes in the surface situation are damped in the solids regarding to the different heat conduction process. On the other hand, in the inverse analysis procedure extrapolates from the interior to the exposed surface, the small experimental errors in the data are magnified at the surface and can lead to oscillations in the estimated surface situations. Some of the procedures have been given to reduce the sensitivity to measurement errors.

In order to determine new heat-shield materials, developing transient calorimeters and trial and testing of rocket nozzles, it is necessary to determine the transient surface heat flux and the surface temperature from a temperature history measured at some location interior to the body. In division of the straight diffusion or transient heat conduction problems this one has been defined as 'inverse problem'. If the thermal characteristics are functions of temperature, then the inverse problem becomes nonlinear. The conventional 'direct problem' of heat conduction is to find the interior temperature distribution of a body from the data given on its surface. While the problem arises where data is not available over the entire surface but is credited at interior points. In this type of conditions it is required to determine necessary parameters. A process to solve the inverse heat transfer problem [IHTP] is important in determining unknown surface temperature and heat flux from predefined values in the body, which are generally measured as a function of space and time, usually under few surface conditions such as re-entry of space vehicle, a direct measurement of surface temperature variation or the heat flux on the surface is almost impossible to be measured, so that prediction of these values can help, depending on the solution of IHTP. With this a number of studies are carried out to solve IHTP. But generally, the accurate solution of IHTP is mathematically examined and verified that does not exist within a contain time depending on the position at which the known value is available.

II. LITERATURE REVIEW:

Chen and Chang [1] developed an accurate and stable method for solving one-dimensional linear inverse heat conduction problems involving the composite slab of two layers. As there is no time step, the present method can directly predict the surface heat flux (or temperature) at a particular time from the transient measured temperature inside solids without step by step calculation in the time domain until the specific time is reached. In other words, the solution of an inverse problem can be exclusively determined when the data at the interior location are known at a particular time. It is not required to calculate all the nodal temperatures at each time step when the present method is applied to the inverse problems. In addition, in this model Beck's sensitivity or a least square criterion required in most previous works is not employed to best match the measurement. Therefore, it can be concluded that the given method is simpler than previous works for same problems. It is also found from the present study that the given method gives a little effect of the measurement location on the estimates. This shows that the present model offers a great deal of flexibility. This method is considerably powerful numerical technique for linear one-dimensional heat conduction problems. Its mathematical formulation is so simple that other geometries in addition to the planar one illustrated here can also be considered.

Jarny et al. [2] proposed a general method for formulating the solution of the inverse heat conduction problem (IHCP) as the solution of infinite dimensional optimization problem (IDOP). In this method it is assumed that there is no a priori information on the nature of the unknown functions to be determined by the inverse analysis. Finite dimensional problems, which are achieved when a priori information is available, become merely other case of the given approach. A common algorithm has been given for solving IHCP by iteration. When the direct problem is found to be linear with the unknown function to be determined, then the functions to be minimized is a quadratic convex, the solution is single and the convergence of the sequence defined by the conjugate gradient method is guaranteed if some regularization is introduced, i.e. if the regularization parameter c is positive. In this case the direct problem is nonlinear with the unknown function; the functions to be minimized may have local minima. The method allows the finding of such minima by changing the initial guess. This method may also be applied to the determination of other properties such as heat capacity, surface temperature. The steady-state inverse heat conduction problems are also a case of the given method.

Huang and Ozisik [3] presented the regular conjugate gradient method for a well-organized, quickly convergent, simple approach of the solution of inverse heat conduction problems given that the final time value of the heat source is available. In such type of situations when the heat source at the final time is not given, the modified conjugate gradient method can be applied to obtain a reasonable estimate for determining the initial guess value to start the iterations in the regular conjugate gradient method.

J. Vogel, L. Sara and L. Krejc, [4] presented a new variable time step method for the one-dimensional inverse heat conduction problem. The main benefit of this algorithm is seen in its ease, computational efficiency and in a good ability to calculate from data with small-amplitude and high-frequency error.

Taler [5] developed an accurate and simple technique which is capable of solving linear inverse heat conduction problems in which the data have random errors. The presented approach uses past and future time data at the same time as it requires no iteration. Regardless of most previous works on inverse heat conduction problems this procedure requires no information about initial temperature distribution in the solid. The surface heat flux at a specific time can be directly calculated from the transient temperature measured inside a solid without step by step computation in the time region. It is not necessary to calculate all the nodal temperatures at each time step to calculate the surface heat flux. In order to obtain results of very good quality, the space domain may be divided only in three or four control volumes. The temperature-time data can be curved using global approximation or moving averaging filters. The presented algorithm is very fast and can be easily extended to multidimensional inverse heat conduction problems.

China JI [6] adopted the recursive least-squares algorithm to examine the estimation of surface heat flux of inverse heat conduction problem from experimental data. The Kalman filtering technique which was used for the residual innovation sequence and the least-squares estimation which accounted for computing heat flux was introduced to solve one-dimensional inverse heat conduction problem. On account of recursive algorithm, an on-line estimation can be used in place of batch form off-line estimation; the method is adequate for impulse heat flux estimation.

A sharp impulse form of input can be determined very precisely by means of the RLSA. The RLSA is sufficient for on-line 1-D inverse heat conduction experimental estimation. The relation between the physical model and the process noise covariance needs further analysis.

Huang and Tsai [7] applied the Conjugate Gradient Method (CGM) along with the Boundary Element Method (BEM) for the solution of the inverse heat conduction problem to determine the unknown transient boundary heat flux in an irregular domain by applying temperature data. Few test cases including different measurement errors and domain shape were considered. The results obtained shows that the inverse solutions obtained by CGM remain stable and regular as the measurement errors are increased and the number of sensor can be minimized.

Taler and Zima [8] presented the new space marching procedure for one and multi dimensional inverse heat conduction problems. The procedure discussed is mathematically simple and computationally competent. To achieve high accuracy of the solution in contrary to the direct problems only a small number of control volumes can be considered. Another unique advantage of the present formulation is that it is non-iterative and non-sequential. Importance of this method is that it requires no information about the initial temperature distribution. The inverse solution developed in this paper depends only on the initial temperature distribution in the direct region. The initial less accuracy is the result of large distance of the temperature sensor from the outer surface and the sudden change of the fluid temperature which make the inverse method inaccurate. When the temperature sensor is located far from the active uncovered surface as in this case then the measured temperature is noticeably delayed and damped in comparison with time changes occurring at the covered surface. Thus, it is impossible to determine accurately the initial situation in the inverse region in this case because the calculated time derivatives of the measured temperature are of less accuracy. The initial temperature distribution in the body could be find out much more precisely if the temperature sensor is located near the active surface.

Muniz [9] proposed the regularization techniques zeroth and first-order Tikhonov regularization technique for solving inverse problem. Previous studies to the solution of this inverse problem evidence its genuine inverse problem. When they treat an inverse problem, they cannot apply a methodology which would seem natural if they were dealing with a well-posed (or direct problem). They have to evaluate all available information about the physical system. The direct problem seems to be best solved if the spectral methodology is applied: the advantage of this formulation consists of its semi-analytical nature. The implicit strategy and regularization techniques adopted in this paper yield good results in reconstructing the initial situations. The discrepancy criterion was efficient to estimate the Lagrange multiplier in the analyzed cases, and it was successfully used for other initial conditions. The chosen methods are suitable for solving the inverse problem.

Huang and Wang [10] applied the CGM along with the CFX4.2 for the solution of the 3-D inverse heat conduction problem to determine the unknown transient boundary heat flux in an irregular domain by utilizing simulated temperature readings obtained from infrared scanners. Some of the test cases involving different measurement errors and heat fluxes were considered. The results obtained show that the inverse solutions obtained by CGM remain stable and regular as the measurement errors are increased. From the numerical test cases in this study they concluded that the use of CFX as the subroutine in the 3-D inverse problem in estimating the unknown boundary heat flux with the CGM has been done successfully. By using the similar algorithm, many practical but difficult 3-D inverse problems can also be solved.

Khalidy [11] proposed an algorithm to estimate the boundary condition (surface temperature and surface heat flux) of a body based on the temperature history by the sensor located inside the body. The method applied does not require any stabilization method when exact data are used to solve the problem. By using noisy data the accuracy and stability of the results are increased by using Savitzky-Gollay digital filter or by replacing the parabolic differential inverse heat conduction by the hyperbolic equation. The proposed methods can also be applied for solving multi-dimensional problems.

Chen et al, [12] applied the hybrid application of the Laplace transform technique and the control volume method in conjunction with a hyperbolic shape function. The main problem in solving the Inverse hyperbolic heat conduction problems is that there are the phenomenon of jump discontinuity, reflection and interaction. It has been seen from three different examples presented in the paper that the stability and accuracy of the estimated results for various boundary conditions are good to compare with the exact result. Hence, the proposed numerical method is efficient and applicable for solving the inverse hyperbolic heat conduction problems.

Alhama [13] applied a variant of the Sequential Function Specification Method together with Numerical simulation method as the numerical method to solve inverse problems associated with the determination of different kinds of incident heat fluxes. In order to perform this, only one network device that generates a piece-wise time-dependent function was required in conjunction with a programming routine. The solution for each case, therefore, takes the form of a piece-wise linear function. The network model required for the numerical NSM is very simple since very few electrical devices are required for its implementation and the mathematical manipulations are made by the circuit resolution code. To test the possibility of the proposed method, several test cases were simulated and solved: (i) constant, (ii) triangular, (iii) sinusoidal and (iv) step waveforms. No prior information was applied as regards the functional forms of the required heat flux. The accuracy and effectiveness of this method was illustrated for both exact and error affected input temperatures. The effect of the parameters random error and number of terms that form the functions on the results were also studied.

Colaco, [14] presented the basic concepts of inverse and optimization problems. Deterministic and stochastic minimization techniques in finite and infinite dimensional domains are reviewed. Profits and losses of each of them are discussed and a hybrid technique is introduced. Applications of the techniques discussed for inverse and optimization problems in heat transfer are presented.

Liu [15] studied an inverse analysis for the unknown heat source function by using the genetic algorithms. A modified genetic algorithm is introduced for solving the inverse heat transfer problem to a reasonable degree of precision. Some empirical results are also provided to illustrate the presented algorithms. As compared to the real-valued genetic algorithm, the modified genetic algorithm fundamentally reduces the computational time for convergence with highly qualitative correct results.

Tanana [16] proposed an order-optimal method of approximately solving an inverse problem for a parabolic equation with variable coefficients. He gives an order-exact estimate for the error of the method. The main problems in the design of heat equipments are those of the mathematical modelling of the heat processes and the optimization of the regime parameters of the supplying heat systems. The necessity of formulating the most precise methods of solving IHPs and estimation of their error appear in various thermal physics investigations. In the mentioned problems, direct temperature measurement on the surfaces of the bodies under investigation is often impossible and, simultaneously, the use of thermocouples makes it possible to measure temperature inside them.

Zhou et al. [17] presented a conjugate gradient method algorithm to get better the heat flux and temperature at the front (heated) surface of a 3D object with temperature-dependent thermo physical properties, based on the temperature and heat flux measurements at the back surface (opposite to the heated surface). The inverse problem is formulated in such a way that the front-surface heat flux is selected as the unknown function to be recovered, and the front surface temperature is calculated as a by-product of the IHCP algorithm. In combination with the CGM iterative numerical procedure, the sensitivity problems and the ad joint problems are formulated for the 3D inverse heat conduction problem. Numerical simulations are conducted to test the presentation of the developed model for two different materials respectively heated by a high-intensity periodic, Gaussian laser beam. The effect of the uncertainties in thermal properties on inverse solutions is also verified. The results show that the 2D heat flux and temperature distributions on the front surface can be reconstructed with high accuracies by applying the 3D inverse algorithm formulated in this work. Investigations are further carried out for the reduction of the number of heat flux sensors required on the back surface. It is shown that high accurate inverse solutions can be obtained based on 10 heat flux measurement data if a two-dimensional polynomial least square fitting technique is utilized to extrapolate the heat flux measurement data over the entire back surface. The excellent numerical results presented in this study demonstrate that the proposed approach is a robust numerical algorithm for the 3D IHCP with temperature-dependent thermo physical properties.

III CONCLUSIONS

A simple practice to solve inverse heat transfer problem is very important in determining unknown surface temperature and heat flux from known values in the body. The literature survey presented here is not complete. However, it is sufficient to serve as an indication of the scope of the research completed so far and to draw attention to the deficiency of our knowledge on the subject of ill posed inverse heat conduction one dimensional problem. As our knowledge of this subject increases, the analytical approach will add more to our basic knowledge of ill-posed inverse heat conduction problem in single dimension.

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