Finding Unknown Surface Temperatures and Heat Fluxes in Steady Heat Conduction

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Summary

We have developed a new direct (non-iterative) methodology for determining unknown temperatures and heat fluxes on surfaces of arbitrarily shaped solid objects where the thermal boundary conditions cannot be measured or evaluated otherwise. The method belongs to a general class of algorithms for the solution of inverse boundary value problems with the objective of determining the unknown boundary conditions. A requirement for this technique to work is that both temperatures and heat fluxes must be available and specified together (creating an over-specified problem) on at least a part of the object's surface. Our inverse algorithm utilizes the boundary element method (BEM). The algorithm computes the temperature field within the entire object and simultaneously calculates temperatures and heat fluxes on surfaces where thermal boundary values are unavailable. Both a two-dimensional and a three-dimensional steady-state BEM programs have been developed and were tested on several simple geometries where the boundary conditions and the analytic solutions were known everywhere. Results were in excellent agreement with the analytic values. The algorithm is highly flexible in treating complex geometries, mixed thermal boundary conditions and temperature-dependent material properties. The accuracy and reliability of this technique deteriorate when the known surface conditions are only slightly over-specified and far from the inaccessible surfaces.

Introduction

The objective of our steady-state inverse heat conduction problem is to deduce temperatures and heat fluxes on any surfaces or surface elements where such information is unknown. It is often difficult and even impossible to place temperature and heat flux sensors and take measurements on a particular surface of a conducting solid due to its small size or geometric inaccessibility or because of the severity of the environment on that surface. With our inverse method these unknown thermal boundary values are deduced from additional temperature or heat flux measurements made at a finite number of points within the solid or on some other surface of the solid. Most of the existing methods for solving such inverse boundary value problems are iterative and based on the one-dimensional transient heat conduction problem. Initial efforts used convolution integrals [1] and were subsequently improved by a number of authors [2]. Many other methods [3] have also been developed using such techniques as Laplace transforms, iterative finite elements [4], time-marching finite differences [5] and other approaches.

In most of these inverse techniques the random noise due to round off errors tends to magnify as the solution proceeds in time and quickly produces a useless solution, especially as the distance between the surface and the over-specified information increases [6]. Various smoothing techniques for reducing this error growth could be used, but the effect of these operations on the accuracy of the solution is not easy to evaluate [7].

The method presented herein does not utilize any artificial smoothing technique and is not limited to transient or one-dimensional problems. Our approach is robust since it is non-iterative. It has been shown [8,9] to compute meaningful and accurate thermal fields in a single analysis using a straight-forward modification to the boundary element method (BEM).

The BEM is a very accurate and efficient technique [10,11] that can solve boundary value problems such as those governing heat conduction, electromagnetic fields, fluid flow, elasticity and many other physical phenomenon. When analyzing steady-state heat conduction using the BEM, either temperatures, T, or heat fluxes, Q, are specified everywhere on the surface of the solid where one of these quantities is known while the other is unknown. When performing an inverse evaluation of the steady-state heat conduction using the BEM, both T and Q must be specified on a part of the solid's surface, while both T and Q are unknown on another part of the surface. Elsewhere on the solid's surface, either T or Q should be applied. The surface section where both T and Q are specified simultaneously is called the over-specified boundary. If temperatures or heat fluxes are known at isolated points within the solid, they can be directly added to the BEM equation set in order to enhance the accuracy of the inverse heat conduction procedure.

Analytical and Numerical Formulations

The governing equation for steady-state heat conduction in a solid with a temperature-dependent coefficient of thermal conductivity is

$$\nabla \bullet \left(k(T)\, \nabla T \right) = 0 \tag{1}$$

where T is the temperature and k(T) is the temperature-dependent coefficient of thermal conductivity. Equation (1) can be linearized by the application of the classical Kirchoff transformation which defines the heat function, u, as

$$u = \int_0^T \frac{k(T)}{k_0}\, dT \tag{2}$$

where k_0 is the reference coefficient of thermal conductivity. Equation (1) is subsequently transformed into Laplace's equation operating on the heat function, u. The boundary integral equation (BIE) for Laplace's Equation is obtained from the weighted residual statement or Green's Theorem

$$c(\xi)u(\xi) + \int_\Gamma u^* q \, d\Gamma = \int_\Gamma q^* u \, d\Gamma \tag{3}$$

where the integration is over the solid surface, Γ. Here, $q = \partial u/\partial n$, u^* is the fundamental solution [10], $q^* = \partial u^*/\partial n$, n is the direction of the outward normal to the surface, Γ, and $c(\xi)$ is a free term arising from the integration over the singularity in the sense of the Cauchy principal value at the point ξ: $c(\xi) = 0.0$ when ξ is outside the domain, $c(\xi) = 1.0$ when ξ is inside the domain, and $c(\xi) = \theta / 2\pi$ when ξ is on the boundary (θ is the internal angle). The fundamental solution is a general Green's function solution for a point-source subject to the homogeneous boundary conditions. For the two-dimensional and three-dimensional Laplace's equation they are

$$u^* = \frac{1}{2\pi} \ln\left(\frac{1}{|\xi - x|}\right) \qquad u^* = \frac{1}{4\pi|\xi - x|} \qquad (4)$$

respectively, where x is the point of integration and ξ is the control node. A set of N boundary integral equations exists for each of the N control nodes on the boundary. The surface integrals over the boundary may be discretized into a number of surface panels connecting the N nodes. The functions u and q are either constant over each panel or they may be linearly, quadratically, etc. distributed over each panel. After adding the contributions from each surface integral, the whole set of boundary integral equations can be written in matrix form.

$$[\mathbf{H}]\,\{\mathbf{U}\} = [\mathbf{G}]\,\{\mathbf{Q}\} \qquad (5)$$

For example, for constant elements the entries to the [**H**] and [**G**] matrices are

$$h_{ij} = \int_{\Gamma_j} q^*\, d\Gamma \qquad g_{ij} = \int_{\Gamma_j} u^*\, d\Gamma \qquad (6)$$

If the domain's surface is discretized with N nodes, initially there will be a total of 2N unknowns in the equation set. For a well-posed boundary value problem, at least one of the functions, u or q, will be known at each boundary node (either Dirichlet or von Neumann boundary condition). After the boundary conditions are applied, the equation set will be composed of N unknowns and N equations.

For example, if we have a four-node domain with Dirichlet boundary conditions specified everywhere on the boundary, the left-hand side of the discretized BIE may be multiplied out to form a vector of knowns, {**F**}, while the right-hand side remains in the form [**A**]{**X**}. The equation set becomes a system of four linear algebraic equations that can be solved for the unknown fluxes by any standard matrix solver such as Gaussian elimination or LU factorization. If the boundary conditions in the above example are not properly applied, the problem becomes ill-posed but a solution may still be obtained. For example, if at two boundary nodes both u = U and q = Q are known but at the other two nodes neither is known, the BIE equation set before any rearrangement appears as

$$\begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{Bmatrix} U_1 \\ u_2 \\ U_3 \\ u_4 \end{Bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & g_{22} & g_{23} & g_{24} \\ g_{31} & g_{32} & g_{33} & g_{34} \\ g_{41} & g_{42} & g_{43} & g_{44} \end{bmatrix} \begin{Bmatrix} Q_1 \\ q_2 \\ Q_3 \\ q_4 \end{Bmatrix} \qquad (7)$$

In order to solve this set, all of the unknowns will be collected on the right-hand side while all of the knowns are assembled on the left. Straight forward algebraic manipulation yields the following set

$$\begin{bmatrix} h_{11} & g_{11} & h_{13} & g_{13} \\ h_{21} & g_{21} & h_{23} & g_{23} \\ h_{31} & g_{31} & h_{33} & g_{33} \\ h_{41} & g_{41} & h_{43} & g_{43} \end{bmatrix} \begin{Bmatrix} U_1 \\ Q_1 \\ U_3 \\ Q_3 \end{Bmatrix} = \begin{bmatrix} h_{12} & g_{12} & h_{14} & g_{14} \\ h_{22} & g_{22} & h_{24} & g_{24} \\ h_{32} & g_{32} & h_{34} & g_{34} \\ h_{42} & g_{42} & h_{44} & g_{44} \end{bmatrix} \begin{Bmatrix} h_2 \\ q_2 \\ h_4 \\ q_4 \end{Bmatrix} = \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{Bmatrix} \qquad (8)$$

Since the vector on the left-hand side is known, it may be multiplied by its coefficient matrix to form a vector of knowns, {**F**}. The right-hand side remains in the form [**A**] {**X**}. At first glance, the solution of this set of linear algebraic equations appears straight-forward but it is not. This equation set is highly singular and most standard matrix solvers will not work well enough to produce a correct solution. Luckily, there exist very powerful techniques for dealing with sets of equations that are either singular or very close to singular. These techniques, known as Singular Value Decomposition (SVD) methods, are widely used in solving most linear least squares problems. Any M x N matrix [**A**] can be written as the product of an M x N column-orthogonal matrix, [**U**], an N x N diagonal matrix [**W**] with positive or zero elements, and the transpose of an N x N orthogonal matrix [**V**].

$$[\mathbf{A}] = [\mathbf{U}] \begin{bmatrix} w_1 & 0 \\ 0 & w_N \end{bmatrix} [\mathbf{V}] \qquad (9)$$

A SVD algorithm [12] was used in this work to solve the equation set and, most often, a solution to the highly singular BIE formulation was obtained. Since the SVD algorithm is capable of solving non-square matrices, the number of unknowns in the equation set need not be the same as the number of equations. Thus, virtually any combination of boundary conditions will yield at least some solution. Also, additional equations may be added to the equation set if, for example, temperature or heat flux measurements are known at locations within the solid domain.

Verification of the Nonlinear BEM Analysis Code

The accuracy of the boundary element analysis program for nonlinear heat conduction was tested on an example consisting of a 1.0 cm long by 0.1 cm high rectangular plate. The plate circumference was discretised with 22 linear surface panels each

0.1 cm in length. The two vertical sides of the plate were kept adiabatic (Q = 0) and the two horizontal sides were subject to different uniform temperatures (T_{hot} = 100 K and T_{cold} = 0 K). The temperature-dependent thermal conductivity was given as a fourth order polynomial function

$$k(T) = k_o (AT^{-1} + B + CT + DT^2 + ET^3) \quad (10)$$

where k_o = 1.0 W/cm K, B = 1.0 and A = D = E = 0. Temperature data was collected for various degrees of non-linearity given by one parameter, C. The results were compared with the one-dimensional analytic solution [13].

$$\frac{C}{2}T^2 + T = \left(T_{hot} + \frac{C}{2}T_{hot}^2\right) - \left(1 + \frac{C}{2}\left(T_{hot} + T_{cold}\right)\right)\frac{\left(z - z_{hot}\right)}{\left(z_{cold} - z_{hot}\right)}\left(T_{hot} - T_{cold}\right)$$

The BEM results compared well with the analytic solution, averaging an error of less than 0.5 %.

The behavior of this analysis algorithm was also examined for steady-state heat conduction in an annular solid disk. The outer radius of the disk was 1.2 cm and the centrally located circular hole had a radius of 0.5 cm. The analytic solution for this problem was developed by applying Dirichlet or essential boundary conditions everywhere on the boundary of the annular region. Temperature boundary conditions of 100°C on the outer boundary and 50°C on the inner boundary were enforced. The thermal conductivity of the solid was considered to be constant, k = 1.0 W/cm°C. The analytic solution for the temperature field within the disk is easily found as

$$T (r) = A + B \log r \quad (12)$$

where A = 89.59 and B = 57.11. The radial heat flux is then

$$Q (r) = - k \nabla T = - k\, dT(r)/dr = B / r \quad (13)$$

which yields Q_{out} = - 47.59 W/cm^2 and Q_{in} = 114.22 W/cm^2 as heat fluxes through the outer and inner boundaries, respectively. The BEM algorithm was run on the same problem. The problem was discretized with 36 panels on outer and 36 panels on inner boundary. The BEM program predicted the temperature field in the annular solid which averaged only a 0.3% error versus the analytic solution.

Testing Inverse Boundary Value Problem Method

A BEM computer program was developed using the theory discussed in this paper. The accuracy of the BEM as a solution to the inverse boundary value problem was first verified for a solid square plate. The plate was 1.0 cm on each side and the thermal conductivity of the plate was chosen as k = 1.0 W/cmK. The top and bottom boundaries were specified to be adiabatic (Q = 0 W/cm^2), while the left side of the plate was over-specified with a temperature boundary condition of T = 1 K and a heat flux boundary condition of Q = 1.0 W/cm^2. The right side of the plate was considered to be inaccessible and, as such, both temperature and heat flux were unknown on this boundary. The plate boundary was discretized with 32 panels (eight panels per each of the four sides). The inverse BEM solution was compared to the analytic solution and was found it to be highly accurate with an error in temperature of less than 0.05% and an error in flux of less than 0.1%.

In order to study the feasibility and accuracy of the BEM solution to the steady-state inverse boundary value problems, several tests were performed utilizing the same annular geometry and outer boundary thermal data in a variety of combinations [8]. We will demonstrate only a few cases here. The circular disk was discretized with 36 panels on both the inner and the outer boundaries. The objective was to find the unknown temperatures and heat fluxes on the inner surface.
Disk-a. Temperature boundary conditions were specified on the entire outer boundary, but the additional heat flux boundary conditions were over-specified in the first and third quadrants of the outer boundary only. The BEM solution set had 54 knowns, 90 unknowns and 72 equations. The temperature field (Figure 1a) compared well with the analytic solution with nearly axisymmetric isotherms. The temperature on the inner boundary was oscillatory, but had an rms error of only 0.85%. The heat flux on the inner boundary was also oscillatory and averaged an rms error of about - 2.0%.
Disk-b. Temperature boundary conditions were specified on the entire outer boundary, while heat flux boundary conditions were over-specified only on the upper half of the outer boundary. As in the previous test, the BEM solution set contained 54 unknowns, 90 unknowns and 72 equations. The temperature field (Figure 1b) was slightly asymmetric about the x-axis, but was very symmetric about the y-axis. The greatest error in the temperature field occurred in the bottom half of the annular solid region. The errors in temperature and heat flux are quite oscillatory in nature and noticeably peak at about 20% at the very bottom of the solid disk (the point farthest from the over-specified data).
Disk-c. This test case is identical to the previous case, except that heat flux boundary conditions are over-specified in the first quadrant of the outer boundary only. The BEM solution set contained 45 knowns, 99 unknowns and 72 equations. The predicted isotherms (Figure 1c) within the solid disk demonstrate that the error in the temperature field obviously worsens as the distance from the over-specified data increases. The error in heat flux is oscillatory and peaks at about 60% at the point farthest from the over-specified data. Notice also that the temperature field is symmetric about the line inclined 45 degrees and passing through the center of the circle.

Sensitivity of the Inverse Boundary Value Method to Measurement Errors in the Boundary Conditions

Next, various degrees of errors were intentionally introduced into the over-specified boundary conditions of the annular disk described in the previous section. The disk was discretized with 36 flat panels on both the outer and inner surfaces. The entire outer surface was over-specified with temperature and heat flux data, while both were unknown on the inner surface. Truly random input errors were introduced into the outer surface data by hand and the outputted temperature and heat fluxes computed by the inverse BEM were observed in terms of their accuracy with respect to the analytic solution.

The results of this analysis indicate that the average computed temperatures and heat fluxes on the inner surface were within less than 0.5% of the analytic solution. Also, the standard deviations of the heat flux errors were always greater than those of temperature. The standard deviation of the output (inner surface) errors stayed at about the same order of magnitude until a standard deviation of 0.1 was reached. Further increase in the input errors had a linear relationship to the increase in the errors in the output values.

The error in the output data as a response to the very small input errors in the boundary temperature data (Figure 2a) is shown to be about two to four times larger than the input error and the temperatures were somewhat biased. The bias was attributed to the fact that flat panels were used to model the circular geometry. In addition, the output errors in both temperature and heat flux were peculiarly sinusoidal in shape for not only small input error magnitudes, but also for larger magnitudes (Figure 2b).

Sensitivity of the output errors to various levels of input errors in heat flux data is shown in Figures 3a-b. When comparing these figures to those of the previous two, the output data is observed to be more sensitive to errors in the input temperature data than to the input heat flux data. In addition, the amplitude of the sinusoidal error in the output was of the same order of magnitude as the input heat flux error.

Testing Inverse Boundary Value Method for Multiply Connected Domains

The feasibility of the inverse boundary value BEM technique in computing unknown temperature and heat flux data on inaccessible surfaces was next demonstrated on a two-dimensional square plate with a single non-centrally located square hole. The plate was specified to be 1.0 cm on each side and the square hole was 0.4 cm on each side. In order to determine if the inverse technique produced correct results, the temperature field within the solid was first determined using a standard BEM analysis with well-posed boundary conditions. The left side of the plate was specified with a temperature of 1 ^{o}C, the right side was specified with a temperature of 0 ^{o}C, the top and bottom sides were specified to be adiabatic and everywhere on the square hole a temperature of 0.5 ^{o}C was specified. As a by-product of this analysis (Figure 3a), the temperatures on the top and the bottom walls and heat fluxes on the side walls of the plate were obtained.

Then, both the temperatures and the heat fluxes were specified on all four sides of the plate and nothing was specified on the four sides of the square hole. The inverse boundary value method solved this problem and the resulting temperature field is practically indistinguishable (Figure 4b) from the one obtained in the preceding analysis (Figure 4a).

A somewhat more practical and complex configuration was tested next that simulated cooling of a simplified electronic chip. The geometry consisted of a rectangular plate with three square holes and six rectangular legs (Figure 5a). First, we analyzed the thermal field in this configuration using our BEM code. Temperatures on the top and bottom surfaces were specified as zero and on the surfaces of the three holes as one. Normal temperature derivatives on the side walls were specified as minus one. The result of this well-specified boundary value problem is shown in Figure 5b. As a by-product of this analysis, we obtained temperatures on the side walls and heat fluxes on the top and bottom walls.

The inverse boundary value problem was then formulated by specifying both temperatures and the temperature normal derivatives on the side walls of the configuration and on the top and bottom walls (surfaces of the six rectangular pins). It was assumed that nothing is known on the surfaces of the three square holes. The resulting thermal field (Figure 4b) is for all practical purposes identical to the thermal field obtained from the well-posed analysis.

Conclusions

We have recently developed a new method that has the capability to determine thermal boundary conditions (temperatures and heat fluxes) on surfaces of conducting solids where such quantities are unknown. The method is extremely fast since it uses a non-iterative direct approach based on the boundary integral method in solving steady-state inverse heat conduction problems of unknown boundary condition type. This means that given any over-specified thermal boundary conditions (such as temperatures and heat fluxes on surfaces where such data are readily available) the algorithm computes the temperature field within the object and any unknown thermal boundary conditions on surfaces where the thermal boundary values are unavailable. A two-dimensional steady-state BEM program has been developed to perform automatic non-iterative determination of both temperatures and heat fluxes on parts of the interior and exterior boundaries. Accuracy of the computer code was tested on several simple geometries where the analytic solution for steady heat conduction was known. Results obtained were in excellent agreement with the analytic values in the regions relatively close to the over-specified data, but deteriorated with the distance from the over-specified boundaries. The method has recently been applied to fully three-dimensional problems.

Our method is exceptionally fast since it is not iterative. For example, a typical two-dimensional BEM analysis or inverse boundary value run consumes about 0.003 seconds. For a typical three-dimensional case with 300 nodes, our BEM run consumes approximately 3.72 seconds. The runs were performed on CRAY Y-90C computer. Consequently, our BEM codes for analysis and inverse boundary value problems can comfortably be used on personal computers.

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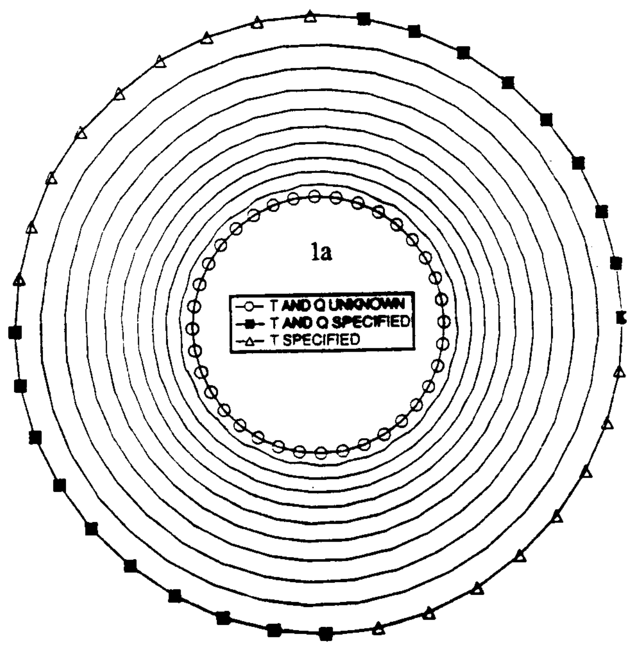
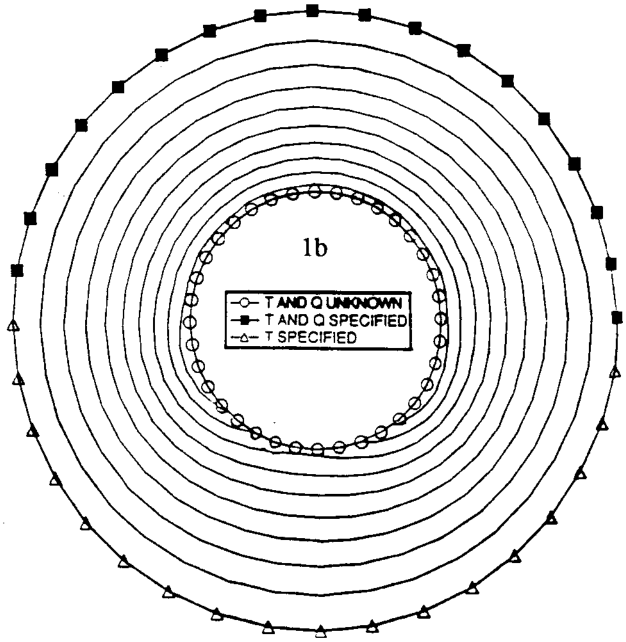




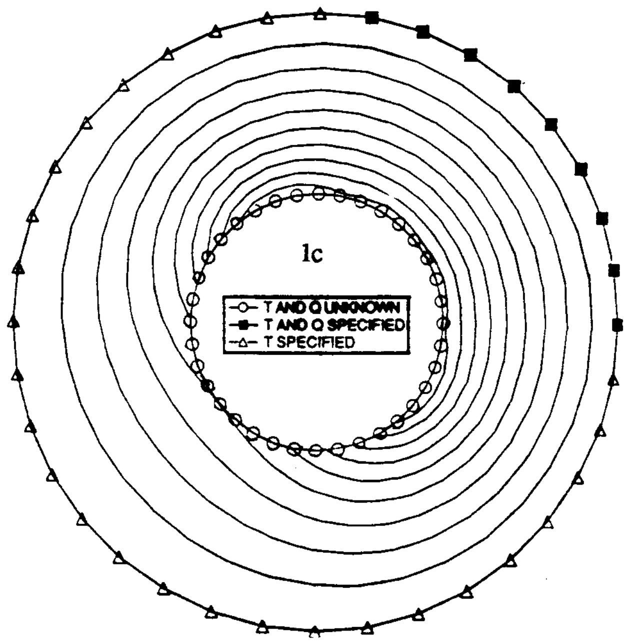
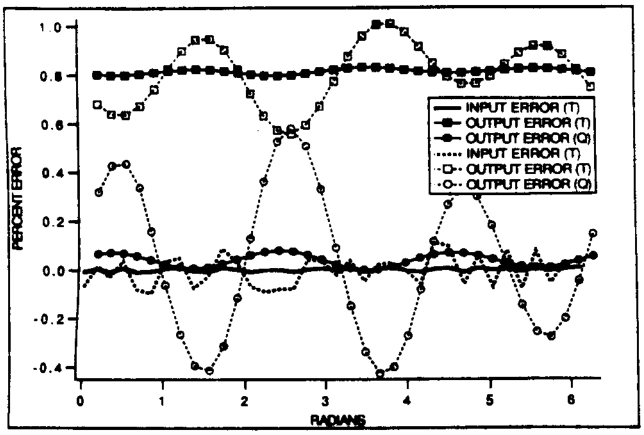


Figure 1. Circular disk: geometry of the BEM nodes on the outer and inner boundaries, boundary condition types and isotherms computed with the BEM for each of the test cases.



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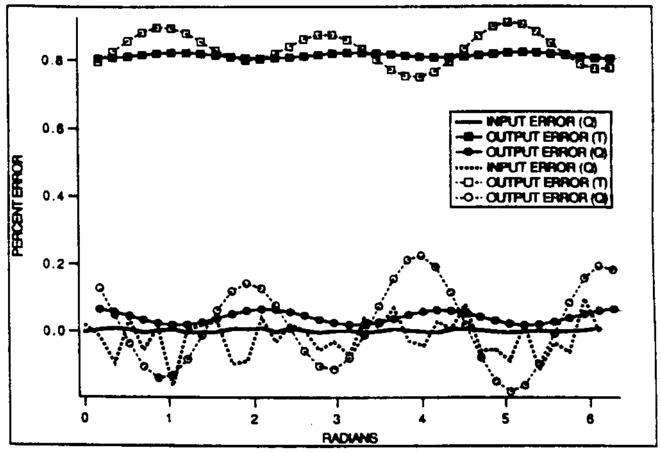

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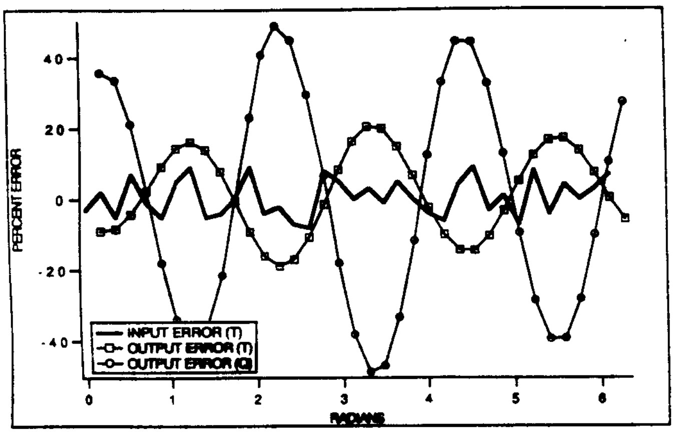

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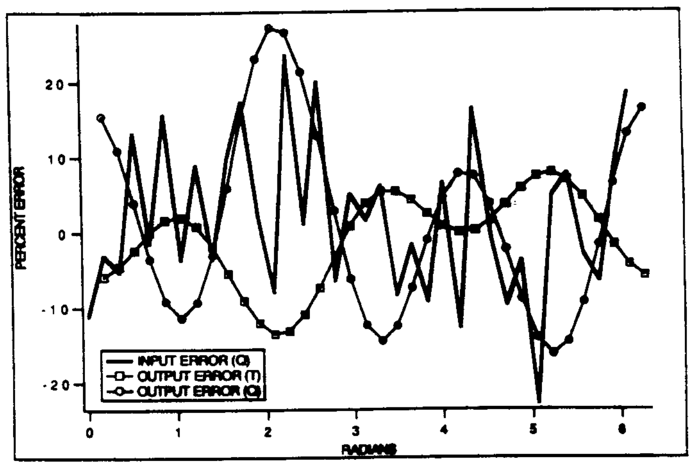
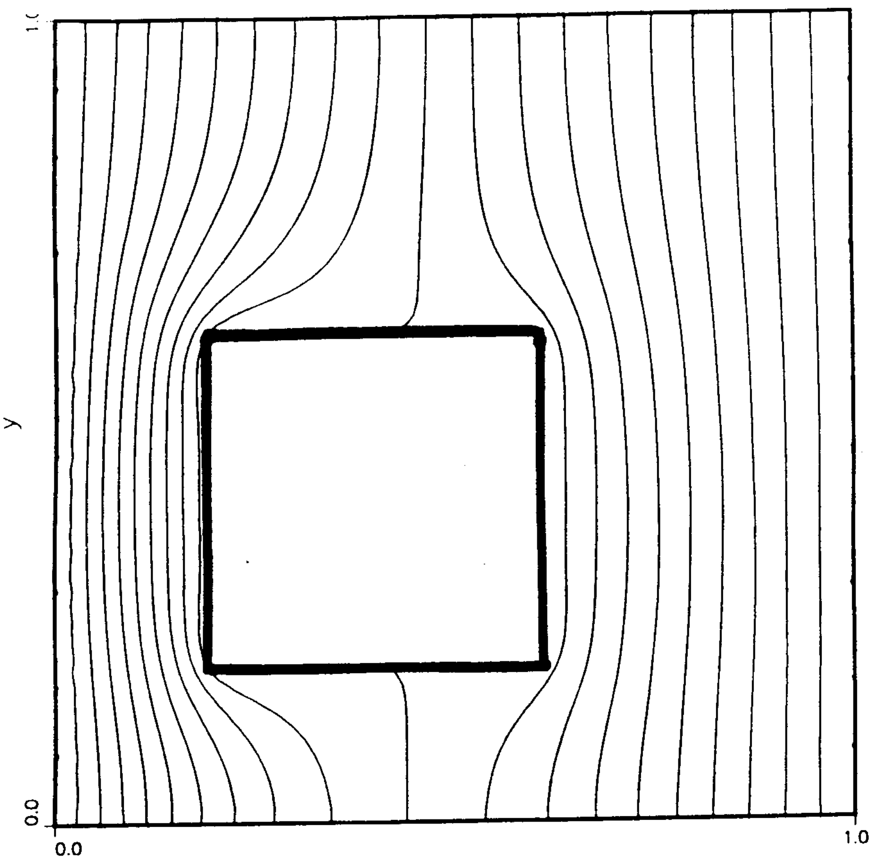


3b

Figure 2. Circular disk: relative percentage errors (inverse BEM versus analytic solution) of the inner boundary temperatures: a) small outside temperatures errors, b) large outside temperature errors.

Figure 3. Circular disk: relative percentage errors (inverse BEM versus analytic solution) of the inner boundary heat fluxes: a) small outside heat flux errors, b) large outside heat flux errors.



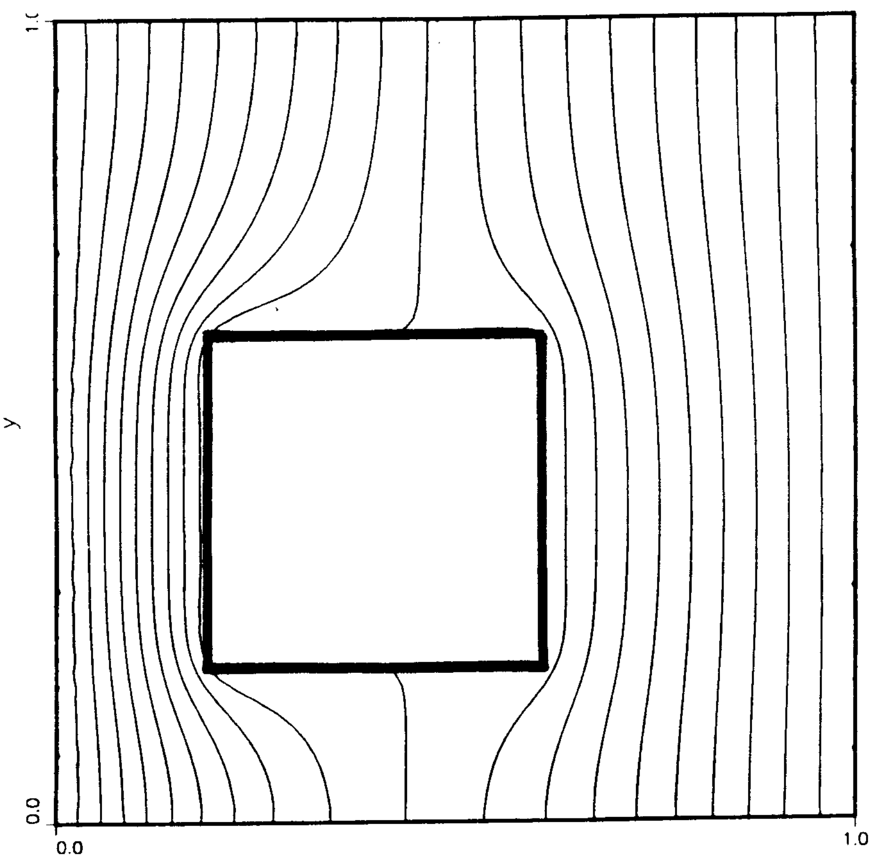
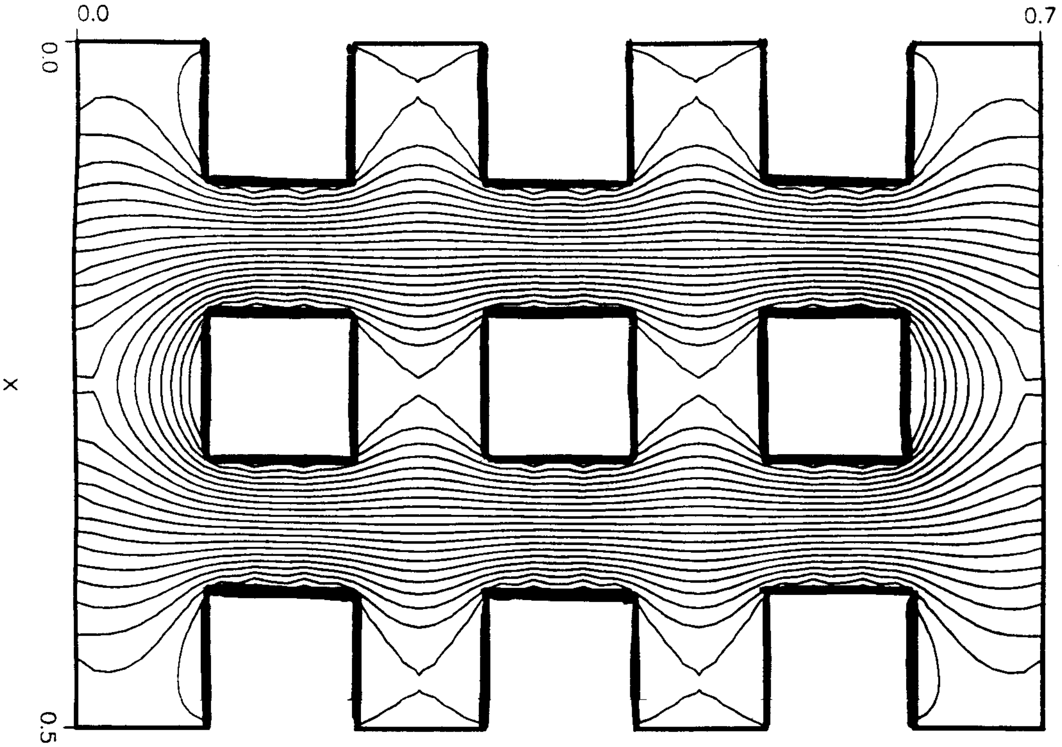


Figure 4. Square plate with a square hole: isotherms obtained with: a) analysis BEM code, b) inverse boundary value BEM code assuming that nothing is known on the hole boundaries.



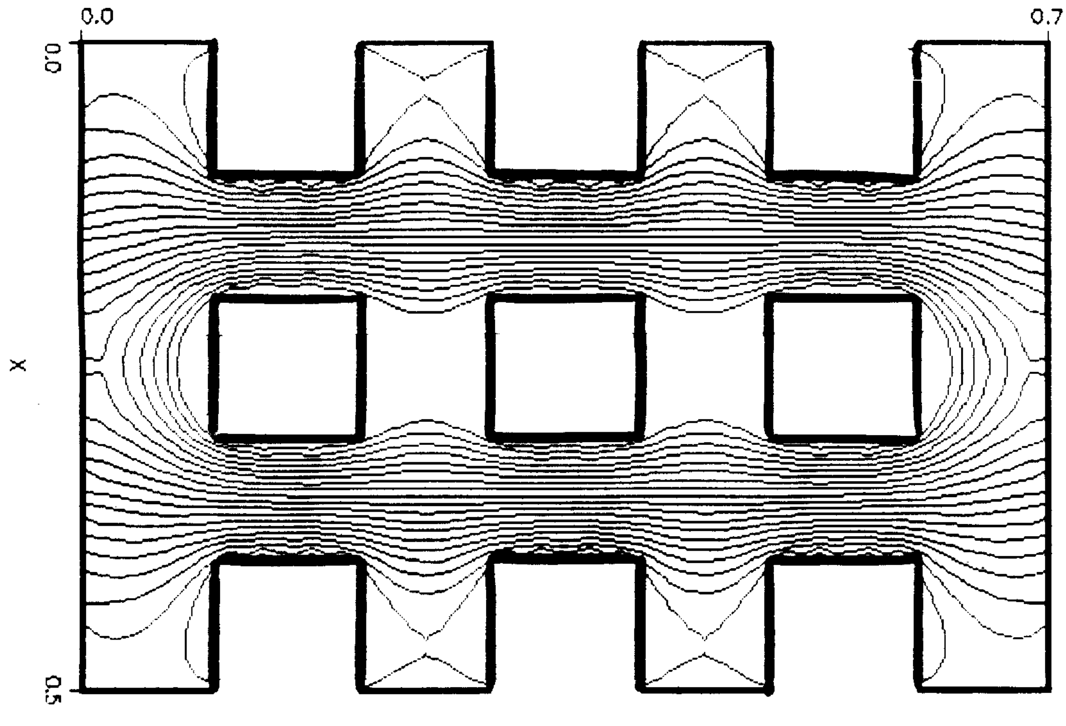


Figure 5. Square plate with three square holes and six pins: isotherms obtained with: a) analysis BEM code, b) inverse boundary value BEM code assuming that nothing is known on the boundaries of the three holes.

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