International Journal of Heat and Mass Transfer 54 (2011) 2514–2524

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A shape design problem in determining the interfacial surface of two bodies based on the desired system heat flux

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ARTICLE INFO

Article history:
Received 14 July 2010
Received in revised form 7 January 2011
Accepted 7 January 2011

Keywords:
System heat flux maximization
Interfacial geometry estimation
Levenberg–Marquardt method
B-spline surface generation

ABSTRACT

A shape design problem (or inverse geometry problem) in determining the geometry of interfacial surface between two conductive bodies in a three-dimensional multiple region domains, based on the desired system heat flux and domain volume, is examined in this study. The design algorithm utilized the Levenberg–Marquardt method (LMM), B-spline surface generation and the commercial software CFD-ACE+. The validity of this shape design analysis is examined using the numerical experiments. Different desired system heat fluxes are considered in the numerical test cases to justify the validity of the present algorithm in solving the three-dimensional shape design problems. Finally, the results show that for the two different cases considered in this work, the maximum increasing in the system heat flux is obtained as 11.3% and 14.1%, respectively. It is also concluded that when the boundary control points of interfacial surface are free to move, maximum system heat flux can be obtained by the present algorithm since it has more degree of freedom in describing the interfacial surface.

1. Introduction

The inverse problems are defined as the problems when one or more conditions are missing in the corresponding direct problems and therefore these kinds of problems are much more difficult to be solved than the direct ones and they are classified as the ill-posed problems. When the geometry of the problem is unknown and to be estimated based on some measurement or desired data, it is named as the shape identification problem or inverse geometry problem.

The shape identification problems, including the shape or cavity estimations, have been solved by a variety of numerical methods. For instance, Burczynski et al. [1] studied the evolutionary computation in optimization and identification. Burczynski et al. [2] used the material derivative-adjoint variable technique and boundary element method to the shape design sensitivity analysis for three- and two-dimensional elastic solid objects. Park and Shin [3] applied the coordinate transformation technique with the adjoint variable method to a shape identification problem in determining unknown boundary configurations for natural convection systems. Huang and Chaing [4] applied SDM to a three-dimensional inverse geometry problem in estimating the shape of boundary surface. Divo et al. [5] applied the singular superposition technique for cavity detection.

Huang and his co-workers have utilized the gradient based algorithm together with the boundary element technique or commercial code CFD-ACE+ [6] to the shape identification problems and have published a series of relevant works for the two-dimensional [7,8] and three-dimensional [9–11] applications. Huang and Chao [7] were the first to derive the formulations for determining the unknown irregular boundary configurations for a 2-D steady-state shape identification problem with the CGM. Huang and Tsai [8] have extended the algorithm to a 2-D transient shape identification problem in finding the unknown irregular boundary configurations from boundary measurements.

Recently, Huang and Chen [9] used the steepest descent method to estimate the space and time-dependent shape of an irregular internal cavity. Huang and Chaing [10] identified the time-dependent irregular boundary configurations in a three dimensional inverse geometry problem. Huang and Liu [11] studied an inverse geometry problem to estimate simultaneously two interfacial configurations in a composite domain.

For the shape identification problem or shape design problem, due to its inherent nature, it requires a complete regeneration of the mesh as the geometry evolves. Moreover, the continuous evolution of the geometry itself poses certain difficulties in arriving at analytical or numerical solutions. For this reason it is necessary to use an efficient technique to handle the problems with irregular surface geometry, especially in a three-dimensional application.

When the measurement data is replaced by some specified conditions, i.e. the design or desired conditions, the above shape identification problems become the shape design problem

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doi:10.1016/j.ijheatmasstransfer.2011.02.010

Nomenclature

B	control point vector
h	heat transfer coefficient
f	functional defined by Eq. (6)
k	thermal conductivity
M, N	basis function
$T(x,y,z)$	estimated temperature
Y_1	desired domain volume
Y_2	desired system heat flux
Greek	
Ω	computational domain
$\Gamma(x,y,z)$	unknown interfacial surface configuration
λ	damping parameter
Ψ	Jacobian matrix
ε	convergence criterion
Superscript	
n	iteration index
Subscripts	
1	region 1
2	region 2

problems. Many applications can be found in engineering, for instance, design of shape of cooling passage in turbine blade [12], design of fuel passage in PEMFC [13], design of hull to minimize the desired wake of ships [14], design of fin shape in different operation conditions [15] and design of shape of interfacial surface between two conductive bodies to minimize the thermal resistance [16], etc.

In reference [16], the authors used a family of tooth-shaped interfaces to model the interfacial surfaces and then try to obtain the optimal shape of interfacial surface which minimized the thermal resistance in a two-dimensional domain. Since the shape of interface is restricted to a tooth shape and this may also restrict some possibility in obtaining the optimal shape of interfacial surface. For this reason the objective of the present shape design problem aims at using the B-spline surface generation technique [17] to describe the interfacial surface in a three-dimensional domain and then try to maximize the system heat flux (same as minimize the system thermal resistance) between two conductive bodies. This kind of technique can be applied readily to the heat sink design problem in industrial applications since more heat can be drawn from a fin with optimum shape of interface under the present consideration.

The interfacial surface is generated using B-spline surface method which enables the surface is completely specified using only a small number of parameters (i.e. the control points). The Levenberg–Marquardt method [18] is then chosen to determine these control points since it has proved to be a powerful algorithm in optimal calculations [14,19,20], especially in parameters estimation.

The direct problem, i.e. giving the shape of interface and calculating the domain temperatures, can be solved by CFD-ACE+ and the calculated results are used in the LMM for shape design calculations. The bridge between CFD-ACE+ and LMM is the INPUT/OUTPUT files, these files should be arranged such that their format can be recognized by both CFD-ACE+ and LMM. A sequence of forward steady-state heat conduction problems is solved by CFD-ACE+ in an effort to update the interfacial geometry by minimizing a residual measuring the difference between estimated and desired physical quantities, such as desired system heat flux and domain volume in the present study.

Finally the solutions of this work with two different arrangements will be illustrated to show the validity of using the LMM in the present three-dimensional shape design problem.

2. The direct problem

The following three-dimensional heat conduction model in a multiple region domain Ω is considered to illustrate the methodology for developing expressions for use to determine the interfacial geometry based on the desired system heat flux and domain volume. The boundary conditions for regions Ω_1 and Ω_2 are assumed insulated at $x = 0$, L_1 and $y = 0$, L_2 and the boundaries

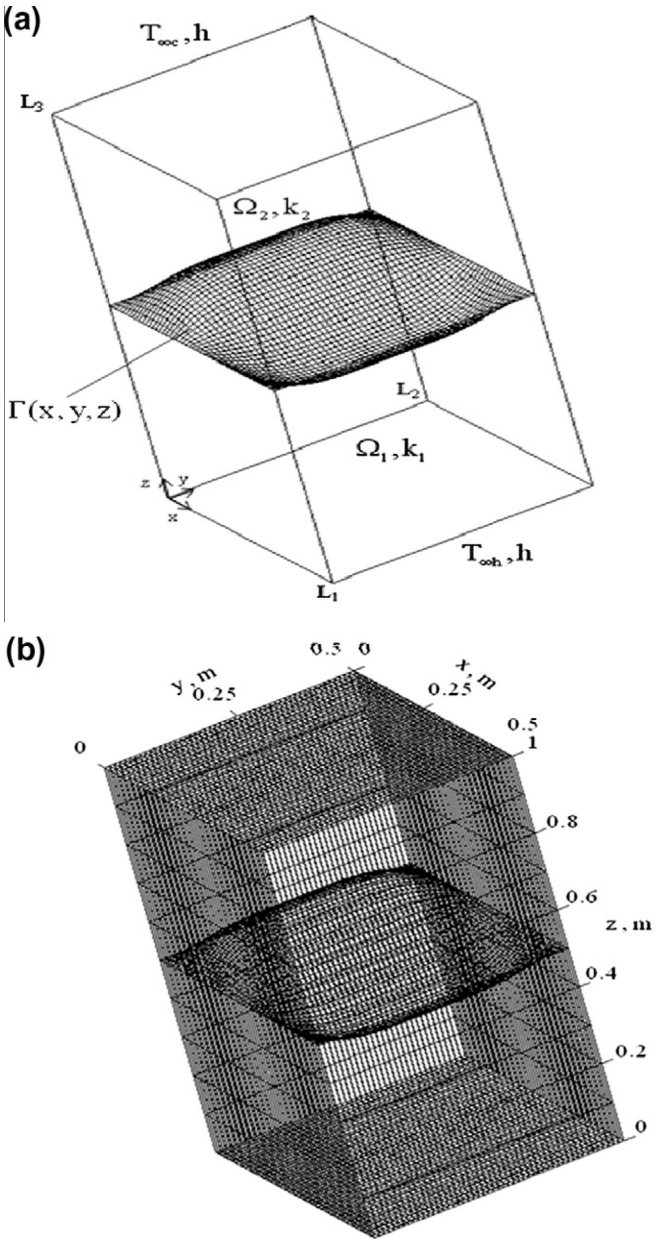

Fig. 1. The (a) geometry and coordinates and (b) grid system for the present study.