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A coupling approach to modeling heat transfer during a full transient flight cycle

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ABSTRACT

The purpose of the present study is to describe novel numerical coupling schemes to analyze the transient temperature field in a solid via a conjugate heat transfer procedure. Emphasis is put on the interfacial treatment based on two complementary treatments: Dirichlet-Robin and Neumann-Robin transmission conditions. The numerical methods are first presented on the basis of a stability analysis in an aerothermal model problem. Stability conditions are expressed and the mathematical expression of the most relevant coupling parameters are provided for the first time. Furthermore, an overview of all the coefficients that can be used in a transient thermally-coupled procedure are given and a unified approach for steady and unsteady ramps is proposed. Then, these interfacial schemes are applied to the problem of convective heat transfer over, and transient conduction heat transfer within, a flat plate. A comparative study with realistic operating conditions is carried out, at low and large Biot numbers. It is shown that certain choices of coupling coefficients, even if physically reasonable, may result in non-converging algorithms. This confirms that a model problem provides insight to the behavior of complicated heat transfer cases and constitutes an invaluable aid for generating efficient interfacial schemes. Indeed, the numerical computations demonstrate the efficiency of the numerical schemes based on the main theoretical results. The trends predicted by the model problem are recovered and excellent convergence properties are observed in all cases.

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1. Introduction

In recent years many studies have been devoted to analyze the behavior of various conjugate heat transfer (CHT) problems, and in general, they are most often limited to steady cases, i.e. when a fluid-solid steady state is sought [1–6]. The simulation of the transient heat load in solid structures is much less common, and the literature on transient CHT has, so far, not been very extensive. It is beginning to be employed in turbomachinery applications to account for the time-dependent thermal response of structures to ambient conditions, for instance in the remarkable pioneering studies at the University of Surrey [7–9]. This approach is essential nowadays to describe accurately the unsteady heat load which could lead to substantial gains in engine performance and component reliability. Note that unsteady CHT is not restricted to turbine blade cooling applications. It can also be found in modeling heating, cooling and ventilating flows in building simulations [10–12].

Unsteady CHT calculations are rather rare in practice because they imply significant computational costs. If in a dynamic coupling, the exchange of information between the fluid and the solid is carried out with a period equal to the fluid time step, transients are calculated and this leads to a very expensive solution, especially over a long period of time. As we are interested here only in the transient temperature analysis in a solid domain, it is clearly not a viable approach to use a transient fluid solution. Accordingly, a two-way coupling of a dynamic thermal modeling in the solid and a sequence of steady states in the fluid is generally considered [7–9,13] to analyze transient conduction. This approach is widely justified by the significant differences between time constants in the two media. It is interesting to note that this quasi-steady approach is also used in other investigations in order to improve the computational time [14–16].

The key point in the coupling implementation is the choice of relevant interfacial conditions. These conditions have a direct

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Nomenclature

a	thermal diffusivity [$m^2\ s^{-1}$]
Bi	Biot number
Bi_Δ	mesh Biot number
C	heat capacity [$W\ s\ K^{-1}$]
D	Fourier number
$\bar{D}$	normalized Fourier number
g	temporal amplification factor
h	heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
K	thermal conductance [$W\ m^{-2}\ K^{-1}$]
L	solid thickness [m]
q	heat flux [$W\ m^{-2}$]
T	temperature [K]
U	velocity [$m\ s^{-1}$]
$y+$	non-dimensional wall distance
z	temporal amplification factor

Greek symbols

α	coupling coefficient [$W\ m^{-2}\ K^{-1}$]
ε	convergence tolerance
κ	spatial amplification factor
λ	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
ν	unit normal vector
ρ	density [$Kg\ m^{-3}$]
Δy	grid size [m]

Subscripts

f	fluid domain
s	solid domain
0+	solid side at the interface
0−	fluid side at the interface

Superscripts

n	temporal index
min	minimum
max	maximum
opt	optimal
$(\hat{\ })$	unknown values

impact on numerical properties of the coupling methodology. However, most of the interfacial numerical treatments in CHT problems are based on a Dirichlet transmission condition (temperature imposed on the fluid side) supposedly due to stability reasons. This was recommended by Giles [1] in a pioneering stability analysis. Yet, it should be kept in mind that three particular conditions were used in his analysis (time-marching procedure in both media, coupling between two unsteady media, update at every time step) and thus it is reasonable to assume that the conclusions of this investigation cannot be extended to all CHT cases. There is ample evidence that there are different levels of dependency between the fluid and the solid and many types of CHT problems can be identified. For instance, as noted by Verstraete et al. [17], at large Biot number, thermal gradients may become important, and thus it seems "natural" to impose a Neumann condition. This is confirmed by CHT test cases [18] and by stability analysis [17,19]. Another recent paper points in this direction. A coupling methodology for weakly transient conjugate heat transfer problems based on two complementary interfacial conditions was proposed by Gimenez et al. [20] and this study showed the interest in using various interfacial conditions. In the same vein, the coupling of a transient solid solution with a sequence of steady states is a very specific issue (neither of the above three particular conditions are met) that needs to be treated as such. Here, we consider this specific problem.

In CHT analysis, adaptive coupling coefficients have been highlighted and expressed for the first time [6]. They are derived from a 1D prototype coupled model in which a numerical transition can be identified. This fundamental result was obtained through a normal mode stability analysis based on the theory of Godunov-Ryabenkii [21–25]. The performance of these coupling coefficients in the framework of a Dirichlet-Robin procedure was tested recently [19,26] and the relevance of the predictive model was fully confirmed. Indeed, the so-called "optimal coefficients" provided oscillation-free solutions and always the smallest convergence rate. Moreover, stability criteria were proposed, for selecting the most relevant interfacial conditions to implement.

However, the previous work was devoted to steady CHT solutions only, and it is not possible to employ this interface model directly. It is then essential to carry out a new stability analysis. The primary goal of this paper is to perform an extensive analysis specially adapted to problems in a full transient flight cycle. In effect, steady and unsteady CHT have very little in common as already outlined in [27,28] where the main numerical characteristics of these two approaches were summarized and compared.

Real-world systems are almost always characterized by multiple interacting physical phenomena and the interactions occur on a wide range of spatial and temporal scales. Therefore, even if the numerical solution of the individual physics is stable and robust, there is no assurance that the coupled system will be also stable and robust. It is common to observe unexpected convergence behaviors (slow convergence, instabilities, oscillations and even bifurcations). This is all the more true in unsteady CHT where this issue is more difficult and sensitive and requires a careful definition of the nature of the thermal coupling implementation at the interface since a relevant fluid-solid solution is required at each time coupling.

The goals of this paper are to propose a numerical methodology, accurate and rapidly converging, to analyze the transient temperature field in a solid via a CHT method and to provide optimal local coefficients at the fluid-solid interface when a transient solid solution is coupled to a sequence of fluid steady states. Two complementary interfacial treatments, namely Dirichlet-Robin (D-R) and Neumann-Robin (N-R) conditions, will be considered.

This paper is structured as follows. The problem specification and the algorithm is presented first (Section 2). Then, two interface treatments are analyzed, their similarities and differences are identified, and emphasis is put on the stability bounds and optimal coefficients (Section 3). On this theoretical basis, a unified treatment to deal with steady and unsteady ramps of a full transient cycle is described (Section 4). Then, a test case is presented (Section 5). A comparative study of convective heat transfer over, and transient conduction within, a flat plate is considered at various operating conditions. The impact on stability and convergence is then described at large (Section 6) and low (Section 7) Biot numbers. At the end of this paper, heteroclite ramps are considered (Section 8).

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