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A coupling numerical methodology for weakly transient conjugate heat transfer problems

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ABSTRACT

This study deals with the development of a partitioned coupling strategy at the fluid–solid interface for weakly transient heat transfer problems. The thermal coupling is carried out by an iterative procedure (strong coupling) between a transient solid and a sequence of steady states in the fluid. Continuity of temperature and heat flux is ensured at each coupling time step.

Emphasis is put on the choice of interface conditions at the fluid–solid interface. Two fluid–solid transmission procedures are considered in this paper: Dirichlet–Robin and Neumann–Robin conditions. These conditions are theoretically examined and it is shown that the *Biot* number is a key parameter for determining relevant interface conditions. Stability diagrams are provided in each case and the most effective coupling coefficients are highlighted and expressed. Numerical thermal computations are then performed for two different *Biot* numbers. They confirm the efficiency of the interface conditions in terms of accuracy, stability and convergence. At the end of this paper a comparison between a partitioned and a monolithic approach is presented.

1. Introduction

The term conjugate heat transfer is used when the two modes of heat transfer – convection and conduction – are considered simultaneously. CHT procedures are today commonly found in many real-world environments in which accurate heat transfer predictions are needed to design efficient cooling or heating systems. The concept of CHT was first introduced by Perelman in the sixties [1].

Mathematically, a CHT problem is composed of a solid domain and a fluid domain, separated by an interface. Mass, momentum and energy conservation equations are solved in the fluid domain. Temperature and flux are continuous at the interface. Numerically, two main strategies can be employed to solve a CHT problem.

The first one is a monolithic approach. The equations are solved simultaneously, that is, they directly operate on the aggregated fluid and solid equations. In other words, the multi-physics interaction is accounted for in a single mathematical model. There are many monolithic solvers that treat coupled problems in this way in mechanical fluid-structure interactions [2,3] or in CHT [4,5]. The main advantage of the monolithic approach is that the mutual influence between the different domains is taken into account directly. This approach has also a positive effect on stability, and no coupling iterations are required within a time step. In this paper, FLUENT capabilities will be used to implement that option.

As opposed to monolithic schemes, partitioned methods allow us to use efficient and specialized codes for each domain [6–9]. For partitioned methods, the physical domain is spatially decomposed into partitions and the solution is advanced in time over each partition. This strategy is very popular because it allows the direct use of specific solvers. Calculation codes communicate by exchanging interface conditions at coupling time steps. In this paper, a finite-volume fluid solver (FLUENT) and a finite-element solid solver (ANSYS) will be coupled to implement that option.

Moreover, strategies taking into account characteristic time discrepancies can be developed, in order to have reasonable computational costs. However, because of the sequential fluid/solid strategy, there is no continuity of flux and temperatures. Appropriate methods must be investigated to ensure flux and temperature continuity at the interface and the choice of interface conditions play a crucial role in stability and convergence speed.

In this study, both approaches will be exploited and compared. It is not our intention to discuss the pros and cons of these methods. Emphasis is clearly put on the definition of relevant conditions at a fluid–solid interface in a partitioned method. The monolithic procedure is just used as a means to evaluate and compare the results in terms of accuracy. A monolithic approach intrinsically

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Nomenclature

a	thermal diffusivity ($m^2\,s^{-1}$)
C_P	heat capacity ($J\,kg^{-1}\,K^{-1}$)
h	convection coefficient ($W\,m^{-2}\,K^{-1}$)
l	flat plate length (m)
L	flat plate thickness (m)
q	heat flux ($W\,m^{-2}$)
T	temperature (K)
T_{ref}	reference temperature at bottom side (K)
U	fluid velocity ($m\,s^{-1}$)
t_c	coupling time step (s)
Bi	Biot number (based on the convection coefficient h)
$\tilde{Bi}$	Biot number (based on the relaxation parameter α)
D	Fourier number
α	coupling relaxation parameter in Robin interface condition ($W\,m^{-2}\,K^{-1}$)
δt_s	solid time discretization (s)
Δt_c	coupling period (s)
Δx	space discretization (length) (m)
Δy	space discretization (width) (m)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	mass density ($kg\,m^{-3}$)

Subscripts

f	fluid domain
s	solid domain
∞	free stream

Superscripts

ν	iteration step in coupling period
n	temporal index in the solid domain
$\overline{()}$	spatial mean quantity
$\hat{()}$	unknown quantity

ensures temperatures and flux continuity at the interface, and does not require the use of interface conditions and interpolations that may result in stability issues. But obviously, a monolithic approach based on the smallest time characteristic is impractical in complex industrial configurations. On the contrary, a partitioned approach based on an appropriate multiphysics strategy could be a viable method.

In recent years, the behavior (well-posedness, stability, convergence) of interface conditions in a CHT procedure in partitioned techniques has been studied in different ways. The most commonly used method is undoubtedly the normal mode analysis [10–14]. On this basis, a transition of the amplification factor was identified recently and as a result, optimal coefficients have been derived in steady CHT procedures [15]. Other models are available such as the energy method [16] or the matrix analysis [17]. This demonstrates that a great deal of effort has been dedicated to determine robust and efficient fluid–solid interface conditions. Therefore, many interesting stability studies are available and nowadays, steady CHT is applied to a great variety of problems.

On the contrary, the simulation of the transient heat load in solid structures via a fluid–solid coupling approach is much less common but starts to be increasingly used. It must be stressed that steady and unsteady CHT procedures have very little in common. These differences have been highlighted in a recent paper [18]. Unsteady CHT occurs for instance in the prediction of the dynamic thermal conditions in building simulations for modeling building heating, cooling and ventilating flows [19–21]. Accurate knowledge of the transient temperature field in the metallic structures plays also a major role, for example in gas turbine design. Recent fundamental studies of transient aerothermal analysis have already been performed [22–24]. These remarkable studies have been conducted through an entire flight cycle. This cycle is generally divided into ramps and in these ramps, linear distributions of the environment parameters are assumed. Each ramp is just a simplified scenario of "steady" or "unsteady" environment conditions. In steady conditions, internal air system conditions may change. The second case generally reflects severe conditions such as engine acceleration or deceleration.

Typically, the influence of unsteadiness in the fluid domain is negligible and the flow field is thus considered as a sequence of steady states. The solid simulation is treated as unsteady for the whole transient cycle. Many authors have already employed this quasi dynamic method [25,26]. Basically, a strong-coupling algorithm is used, i.e., additional iterations are introduced to obtain a converged solution at each coupling time step [27,28].

The choice of relevant interface conditions in terms of stability and convergence speed is one of the main issues of partitioned methods. However few studies have been devoted to study interface conditions in transient CHT problems. The objective of this paper is to investigate numerically these conditions in the case of quasi-dynamic conditions. This work is based on Verstraete theory [29], initially developed for steady CHT problems. One of the goals of this paper is to extend the validity of this approach to weakly transient CHT problems.

2. Quasi-dynamic coupling strategy

2.1. Coupling algorithm

The convective time scale is approximately $\tau_{fluid} = \frac{L}{U}$, and the solid diffusive time scale may be expressed as $\tau_{solid} = \frac{L^2}{a}$. Hence the solid–fluid time scale ratio is $\frac{\tau_{solid}}{\tau_{fluid}} = \frac{LU}{a}$. This ratio is in general very high, for instance in turbomachinery applications. Thus it is possible to assume that the influence of unsteadiness in the fluid domain is negligible and as a result, the flow field may be considered as a sequence of steady states. That is why it is legitimate to couple steady fluid calculations with transient solid calculations. This partitioned coupled method is called quasi dynamic [27], in which each subsystem is represented by an individual solution scheme. Note that if the solid–fluid time scale ratio decreases (for example in natural convection), the unsteady response of the fluid cannot be neglected anymore. In that case, transient calculations have to be performed in both the fluid and solid domains.

The quasi dynamic method is initialized by a steady fluid calculation, performed at the instant $t = 0$, with the initial temperature of the solid imposed at the fluid interface. After convergence of this initial fluid calculation, interface conditions are given to the solid, for the beginning of the first coupling period.

Each coupling period, illustrated in Fig. 1 for a time period between t_c and $t_c + \Delta t_c$, is composed of 4 steps.

The coupling period $t_{\triangle}c$ is divided into several solid time increments $\delta t_s(\Delta t_c = n\delta t_s)$.

Each coupling period is repeated until continuity of fluid and solid fluxes and temperatures at the interface, at every coupling