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Efficiency of coupling schemes for the treatment of steady state fluid-structure thermal interactions

Roch R. El Khoury [a, *], Marc Errera [b], Khalil El Khoury [a], Maroun Nemer [a]

[a] Centre for Energy Efficiency of Systems(CES), MINES ParisTech, PSL Research University, 5 rue Léon Blum, 91120 Palaiseau, France
[b] ONERA, The French Aerospace Lab, 29 Avenue de la Division Leclerc, 92322 Châtillon Cedex, France

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ABSTRACT

Partitioned approaches for the simulation of coupled conjugate heat transfer are gaining popularity in fields that require accurate thermal predictions. Considerable efforts have been put into determining stable coupling schemes, but performance enhancements have been neglected. This paper presents, for the first time, a detailed and comprehensive study of the numerical properties of Dirichlet-Robin coupling procedures, used in conjugate heat transfer simulation, with emphasis put on the optimal local coupling formulation that was recently derived from a stability analysis. This all-new optimal coupling approach provides local adaptability and has never been tested on a complex setup. This investigation looks to determine the relevance and the limitations of the theory when applied to complex conjugate heat transfer setups. The stability theory of the optimal Dirichlet-Robin coupling scheme is first recalled, then, a realistic 3D application, with complex geometry and flow structures, is used to evaluate the performance and sensitivity of Dirichlet-Robin couplings, with respect to various numerical parameters. This detailed study allows, for the first time, to evaluate the advantages and limitations of the recently proposed optimal procedure, when used on realistic 3D CHT problems. It turns out that the local optimal Dirichlet-Robin formulation outperforms all what is found in literature, and insures unconditional stability with monotone convergence for all considered setups of the 3D model.

1. Introduction

Increasing demands for lowering energy consumption and pollutant emissions, as well as improving the quality of the product and the underlying process, has pushed industries to resort to numerical simulation to examine heat transfer processes inside their facilities, where thermal interactions between fluid flow and conduction in solids play an important role in the steady-state heat transfer.

The coupled interaction between conduction in solids and convection in the fluid can only be modelled using procedures in which interface fluxes and temperature distributions are concurrently evaluated for both computational domains. The ability to simultaneously compute these two modes of heat transfer is generally referred to as conjugate heat transfer (CHT) modelling. Numerical CHT has been applied to a great variety of problems using various numerical methods. First reported applications addressed steady-state CHT in turbine blades [14] [17]. Since then, CHT has increasingly been used in a large variety of engineering areas, ranging from building energy simulation [34] [35], to automotive thermal management [21] [12] and thermo-mechanical simulation of turbine stage disks [32].

CHT problems belong to the surface coupled class of multi-physical systems that can be simulated using monolithic or partitioned approaches. Partitioned approaches, reported in Refs. [6] and [25] have proven their superior flexibility and performance, as they resort to existing solvers to separately address the fluid and solid sub-systems. By splitting the problem, an additional common interface is created between the physical domains, through which energy is exchanged, to allow the sub-systems to interact and yield a coupled solution of the CHT problem. Stability, convergence and well-posedness of such interface partitioned coupling schemes, in steady-state and transient CHT procedures, have been extensively studied using normal mode analysis [9] [27] [13] [18] [16], the energy method [23] and matrix analysis [28].

Most CHT procedures reported in literature, impose a temperature boundary condition (Dirichlet) on the fluid side of the

* Corresponding author.
E-mail address: roch.khoury@gmail.com (R.R. El Khoury).

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interface, and a pure heat flux condition (Neumann) or a relaxed one (Robin) on the solid side. The Dirichlet-Robin coupling schemes were shown to offer many attractive features [28] [4] [2]. Their only downside lies in choosing the suitable relaxation parameter that satisfies the stability and the fast convergence rate of the coupled problem. Coupling strategies of partitioned CHT remain an important issue and great efforts have been dedicated to determining robust and efficient fluid-solid interface coupling schemes.

Recently in Ref. [4], on the basis of a 1D discrete thermal model problem, the authors have highlighted that in thermally coupled systems, there exists an optimal choice of the Robin coupling coefficient in terms of stability and convergence of the CHT problem. This optimal coefficient has a local formulation that reflects the main characteristics of the numerical CHT problem.

Our emphasis hereafter is to analyse the numerical properties of the so-called optimal coefficient when applied to a real life 3D model, with complex geometry and flow structures. A comprehensive and comparative study of different values of the coupling coefficient is conducted. The results of the coupled procedure are compared to those obtained using a single integrated solver for the numerical validation of the approach. The detailed study presented in this paper allows, for the first time, to evaluate the advantages and limitations of this promising new coupling scheme for realistic 3D CHT problems.

This paper is organized as follows: section 2 addresses the Dirichlet-Robin coupling procedure for fluid-solid thermal interactions. The stability analysis of the 1D discretized thermal equations of the coupled problem, and the optimal formulation of the local Robin coupling coefficient are recalled. In section 3, a realistic 3D model is introduced. It serves to evaluate the performance and sensitivity of the coupled Dirichlet-Robin procedure to various numerical parameters.

2. Optimal Dirichlet-Robin coupling

2.1. Fluid-solid solution strategy

The CHT modelling strategy employed in this study is motivated by the desire to obtain a fast coupled fluid-structure steady-state solution, for large scale 3D thermal problems. Steady-state heat diffusion, with appropriate boundary conditions, is solved in the solid domain. Disregarding the transient term of the heat equation allows a stable and fast convergence of the thermal boundary problem on the solid side. The same does not precisely apply to the fluid sub-problem, where a steady-state solution can be more efficiently achieved using a pseudo-transient procedure [19]. In fact, most CFD packages, provide algorithms that produce a steady-state solution of the Navier-Stokes (NS) equations using an implicit time marching scheme. As time-accurate solution of the CHT problem is not of interest, the steady-state fluid-solid numerical coupling strategy is based on a hybrid partitioned approach. A pseudo-transient CFD procedure in the fluid and a steady procedure in the solid, are coupled to achieve a coupled steady-state numerical CHT solution.

2.2. The 1D model problem

The characteristics of the numerical methods used in each sub-domain, the exchanged properties at the common interface and the coupling algorithm, are the major contributors to the global behaviour of the coupled CHT procedure. For the sake of simplicity and clarity, we start by briefly describing the aero-thermal 1D model problem that serves as a guide to study the behaviour of the interface coupled fluid-solid thermal problem. The results for the 1D model will provide a valuable insight to understanding the behaviour of the coupling procedure when applied to the 3D real-life setup.

The 1D discrete CHT problem is schematically represented in Fig. 1 where Ω_s and Ω_f are the solid and fluid sub-domains respectively. Δx_s and Δx_f are the constant space discretization steps in Ω_s and Ω_f respectively. The N-S equations in Ω_f are discretized via a finite volume method (FVM) with a pseudo-transient implicit formulation, while heat conduction in Ω_s is solved using a finite element method (FEM) with a steady-state formulation. The solution of the coupled problem is achieved by sequentially solving each sub-problem separately, while keeping fixed the interface values provided by the other one. The newly obtained values at the interface are then transferred to the other solver in order to recompute its own unknowns. The process is carried out until continuous temperature and heat flux is achieved at both sides of the common interface "0".

2.3. Dirichlet-Robin interface transmission procedure

At each coupling iteration, the formulation of the coupling conditions exchanged at the common interface $(x = 0)$ can be written as:

$$T_{0^-} = T_{0^+} \quad in \quad \Omega_f \tag{1}$$

$$q_{0^-} = -q_{0^+} + \alpha_f (T_{0^-} - T_1) \quad with \quad \alpha_f \geq 0 \quad in \quad \Omega_s \tag{2}$$

In the equations above 0^- denotes the solid side of the interface and 0^+ designates its fluid side. Robin condition on the solid side (0^-) of the interface introduces a dose of relaxation, and has many attractive features as it can always be formulated in such a way that the associated local problem is well posed, whereas the Neumann problem is not. Furthermore, the use of such a condition highlights an interface stiffness forcing the boundary of one sub-domain to behave in the same way as the other side [28] [4] [2]. α_f is a numerical coupling parameter with the same dimensions as a heat transfer coefficient $(W.m^{-2}.K^{-1})$. The challenge in such coupling schemes lies in choosing suitable values of α_f that guarantee stability and fast convergence of the coupled problem.

2.4. Coupled model equations

The conventional sequential staggered algorithm consists of 4 stages between two coupling steps defined as the bounds of the interval $[t^n, t^{n+1}]$.

Step 1: The solid temperature of the interface is applied on Ω_f as a Dirichlet condition.
Step 2: The flow solution is advanced by one time-step to obtain the new temperature field in Ω_f under the Dirichlet condition. If the fluid mesh is dense enough to neglect the convection effects in the near-wall cells, the coupled thermal problem in Ω_f can be simplified and modelled by a simple thermal diffusion equation in the fluid, by dropping the advection term from the energy equation. The two steps performed in Ω_f can thus be written under:

$$\begin{cases} T_{0^+}^{n+1} = T_{0^-}^{n} \quad for\ j = 0^+ \quad (Step\ 1) \\ T_j^{n+1} - T_j^n = D_f \left(T_{j+1}^{n+1} - 2T_j^{n+1} + T_{j-1}^{n+1} \right) \quad for\ j > 0^+ \quad (Step\ 2) \end{cases} \tag{3}$$

where $T_j^n = T(j\Delta x_f, n\Delta t_f)$ and D_f is a fluid side, mesh based Fourier number that characterizes heat conduction in the fluid. Using the