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Finite element model reduction for space thermal analysis

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ABSTRACT

To alleviate the computational burden of the finite element method for thermal analyses involving conduction and radiation, this paper proposes an automatic conductive-radiative reduction process based on the clustering of a detailed mesh coming from a structural model for instance. The proposed method leads to a significant reduction of the number of radiative exchange factors (REFs) to compute and size of the corresponding matrix. It further keeps accurate conduction information by introducing the concept of physically meaningful super nodes. The REFs between the super nodes are computed through Monte Carlo ray-tracing on the partitioned mesh, preserving the versatility of the method. The resulting conductive-radiative reduced model is solved using standard iterative techniques and the detailed mesh temperatures can be recovered from the super nodes temperatures for further thermo-mechanical analysis. The proposed method is applied to a structural component of the Meteosat Third Generation mission and is benchmarked against ESATAN-TMS, the standard thermal analysis software used in the European aerospace industry.

1. Introduction

The finite element method (FEM) is widely used in mechanical engineering, in particular for space structure design but not yet often for thermal engineering of space structures where the lumped parameter method (LPM) is still dominant [1–3]. The main reason preventing the use of the FEM is the presence of radiative heat transfer involving huge non sparse matrices containing the radiative exchange factors (REFs). Temperature fields being usually smoother than mechanical stress fields, space structure thermal models are hundreds or thousands times smaller than mechanical models in terms of number of nodes. The number of REFs being proportional to the square of the number of external element faces, this translates into a reduction of 10^4 to 10^6 in terms of number of REFs to compute.

Able to deal with realistic surface properties, the most general and efficient method to compute REFs is Monte Carlo ray tracing [4–6]. This method is however very computationally expensive due to the large number elements composing a FE model and the large number of rays to be fired to have meaningful REF results. Another disadvantage of the FEM occurs when collimated irradiation is specularly reflected by curved surfaces such as mirrors. Potential concentration effects are not well captured if the curved surface is mesh with classical linear element involving flat faces and considering quadratic elements as in [7] drastically increases intersection computation time.

Two approaches can be considered to alleviate these problems: either reduce the number of rays fired from each face for a given accuracy and confidence level or decrease the number of faces by grouping the FE external facets into clusters. Reference [8] focused on the first approach and proposes a method to accelerate the ray-tracing process. This paper focuses on the second approach. As introduced above, the temperature field is usually much smoother than the deformation field and the thermal model therefore requires a much coarser mesh than a mechanical model. Finite element mesh clustering is therefore a natural way to reduce the number of REFs to compute and the size of the associated non-sparse matrix.

Mesh clustering is already used in a variety of mesh-based scientific simulations to reduce computation time by taking advantage of parallel computing [9–12] but also in reverse engineering to retrieve surface properties from scanned data [13]. The idea of creating patches for radiative heat transfer analyses with FEM has been around for quite some time. The method described in [14] is however not based on Monte Carlo ray-tracing to compute the radiation coupling between the patches but on the more restrictive Oppenheim's radiosity method [15]. The method presented in [14] further needs corrective terms to

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cancel false diffusion effects due to the redistribution of the reduced radiation coupling to the underlying mesh since the model is solved on the detailed mesh.

Some other finite element based codes were proposed [16,2] but still use a different mesh than the structural model and therefore require a manual thermal model mesh generation step while giving poor conductive link results due to the low number the number of elements used in practice to limit the REFs computation time.

Over the years, in spite of the advances in computational techniques and numerical analysis, the increasing complexity of scientific and engineering problems gave rise to many reduction techniques to overcome the curse of dimensionality. One of the most influential model reduction technique initially developed for structural analysis is the sub-structuring or *Component Mode Synthesis* (CMS) technique introduced by Hurty [17,18] in the 1960s. Most famous versions of CMS are that of Guyan [19] that includes only static response, Craig-Bampton [20] which consists in the extension of Guyan's method by including internal vibration modes with fixed interfaces or MacNeal [21] that is similar to Craig-Bampton's but uses free-vibration modes. These methods are still widely used today for linear systems. In [22], CMS is applied to the linear transient thermal analysis of a turbine disc and their method was improved in [23] and [24] to compute on-line thermal stresses taking into account non-linear effects caused by convection. They however relied on the off-line computation of the step response using the full model. In [25,26], the linear reduced basis is enriched with, e.g., modal derivatives, but several iterations are required to converge to an adequate basis. There exist other modal bases including nodal temperature derivatives [27] or trajectory piecewise linearisation [28]. The *Modal Identification Method* (MIM) introduced in linear heat conduction [29,30] relies on an optimisation problem to match the parameters of the reduced model to the full model, the reduced model being expressed following the same structure of equation as the full model written in its modal base. This modal superposition technique was applied to several problem in heat transfer [31,32]. This technique was also applied to non-linear heat conduction in [33] and to heat conduction with radiative heat transfer boundary conditions in [34] but also requires the computation of the full model in the optimisation step. Alternative projection methods were proposed in the literature. The *Proper Orthogonal Decomposition* (POD also known as the Karhunen-Love decomposition (KLD) [35]) relies on the separation of the physical space and exploits snapshots of the detailed solution to derive an optimal basis corresponding to a specific load case. The POD was applied in numerous cases [36–42] including thermo-mechanical reduction with radiative boundary conditions [43]. POD was also applied to Monte Carlo simulation of radiation in [44] but only considers small variation of the input. In [45], the MIM and POD methods are compared on a non-linear diffusive system and give similar performances. In [46], POD is combined to the CMS method by replacing the component modes are by the proper orthogonal modes to generate a reduced model of a microelectromechanical system. This method however proved inaccurate when the input differs from the one used for the snapshot generation. To increase the accuracy of the reduced model response to different inputs of a transient non-linear heat conduction model, Binion and Chen [47] use Krylov subspaces to enhance the POD. Recently, *Branch Eigenmodes Reduction Method* (BERM) which relies on particular modes called branch modes [48–50] was developed. The particularity of the branch modes is that they do not depend on the boundary conditions. In [51], BERM is combined with CMS to overcome the difficulty of obtaining the branch basis with large models. While POD can be considered as an *a posteriori* model reduction technique, the *Proper Generalized Decomposition* (PGD) is viewed as an *a priori* model reduction technique [52–55] avoiding any knowledge on the detailed solution in contrast to the vast majority of POD based model reduction techniques. PGD was introduced in computational solid mechanics by Ladevze et al. in the mid 1980s [56–58] and also relies on the separated representation of the problem, like POD. In [59], PGD is applied to thermal model reduction in the frequency domain for real-time thermal process monitoring. Other approaches were proposed such as Latin Hypercube sampling with Gaussian process regression of the detailed model [60] or the grey-box reduction method for non-linear systems [61]. All these techniques, either rely on the computation of the detailed solution or at least on the availability of the detailed model matrices, in particular the radiation matrix which is exactly what we want to reduce.

In this paper, the idea behind the clustering process is to use the mesh of the structural finite element model. Using the same mesh for structural and thermal analyses rather than building a separate model would first reduce the thermal model pre-processing time but also smooth the thermo-structural analysis process [62], being of paramount importance for space structure design [3], without awkward extrapolation of the temperature coming from a coarser mesh and a different method. The proposed method uses the detailed mesh clustering to reduce the radiative terms and introduces the concept of super nodes associated to the clusters for the conductive reduction. Prior to the clustering step, specific critical surfaces can be fitted with quadrics to increase the accuracy of the ray-tracing, in particular when specular surfaces impinged by collimated environmental heat fluxes such as sunlight need to be computed. After the generation of the reduced radiative and conductive links between the super nodes, the coupled reduced model is solved to get the super nodes temperature. The temperatures of the underlying detailed structural finite element mesh are then recovered from the super nodes temperature using the inverse reduction procedure and ready to be used for the thermo-structural analysis. Fig. 1 summarises the global reduction process. A potential automatic iterative process could be envisaged as indicated by the dotted arrow.

The paper is organised as follows. The mesh clustering process used for the radiative reduction is described in Section 2. The conductive reduction process with the definition of super nodes is developed in Section 3. The method is first applied to a one-dimensional beam example in Section 4.1 and a two-dimensional radiating fin in Section 4.2 before continuing with the support structure of the Back Telescope Assembly on-board Meteosat Third Generation in Section 4.3. The conclusions and perspectives of the research are summarised in Section 5.

2. Reduction of the radiative model: clustering process

This section presents the clustering process, starting point towards

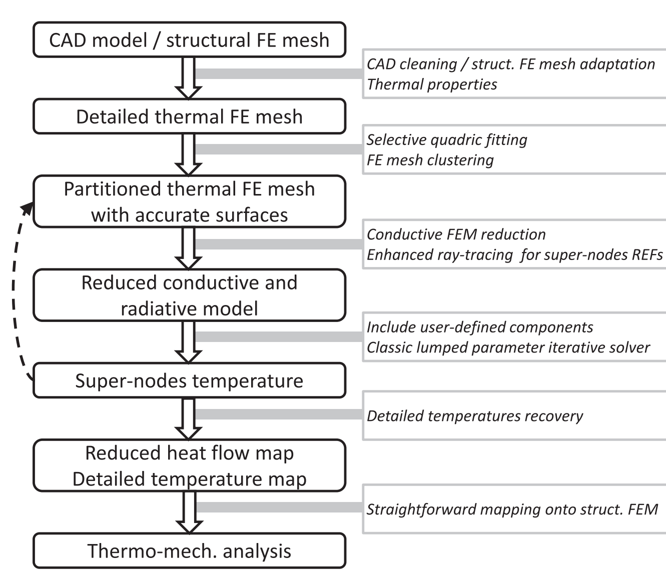

Fig. 1. Global conductive-radiative reduction flowchart.