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Direct simulation for CAD models undergoing parametric modifications[☆]

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ABSTRACT

We propose a novel approach—*direct simulation*—for interactive simulation with accuracy control, for CAD models undergoing parametric modifications which leave Dirichlet boundary conditions unchanged. This is achieved by computing *offline* a generic solution as a function of the *design modification parameters*. Using this parametric expression, each time the model parameters are edited, the associated simulation solution for this model instance can be cheaply and quickly computed *online* by evaluating the derived parametric solution for these parameter values. The proposed approach furthermore works for models undergoing topological changes, and does not need any mesh regeneration or mesh mapping. These results are achieved by use of the *proper generalized decomposition* model reduction technique, in combination with R-functions. We believe this is the first approach that can interactively simulate the physical properties of a CAD model, even undergoing topological change, without expensive re-computation. The approach is demonstrated for linear elasticity analysis; numerical results demonstrate its simulation accuracy and efficiency in comparison with the classic FE method.

1. Introduction

A CAD model typically goes through many design modifications, each time requiring simulation of its physical properties and functionality, before finally being manufactured into an engineered product. The model modifications are in many cases defined or controlled via various shape or feature parameters, describing their locations, sizes etc. Each time the model is modified, its physical behavior are typically recomputed by performing classical FE analysis (or some variant) on the new model. This cycle of design and simulation is computationally expensive, involving volume mesh generation anew from the CAD model, physical solution computation, geometric mapping between the CAD model and the FE volume mesh and so on [1,2]. To make analysis and meshing tractable, the model may also need to be simplified and features removed [3,4]. This overall process of CAD–CAE integration occupies a significant proportion of conventional engineering design process time.

It would greatly facilitate the product design process if the model's physical properties could be rapidly and interactively (within 10 ms, for example) predicted as soon as the design model is modified—we refer to this goal as *direct simulation* here. Such direct simulation is however very challenging to achieve via the traditional complex CAD–CAE integration process, especially as the model's topology may change when feature interactions occur as a result of parameter modification. Consider for example the model in Fig. 1. The original model has two square holes H_1, H_2 with side lengths 0.4, 0.2 within its interior, respectively centered at $(p, 0.5)$ and $(1.5, 0.5)$, where p is a parameter. As p changes from -0.2 to 3.2, moving the center of hole H_1 the x-direction, the resulting model undergoes topological change. Direct simulation aims to interactively predict the modified model's physical properties, for example point-wise displacement in an elasticity analysis, as the designer moves feature H_1. No existing simulation approach can directly handle such complex cases involving topological change.

This challenging task of direct simulation for CAD models undergoing parametric modifications cannot readily be solved by classical model reduction techniques, such as POD (proper orthogonal decomposition) [5], subspace methods [6], or PCA (principle component analysis) [7]. Such techniques essentially approximate the target physical property space by a linear space using a basis set, using e.g. the eigenvectors of some sampled

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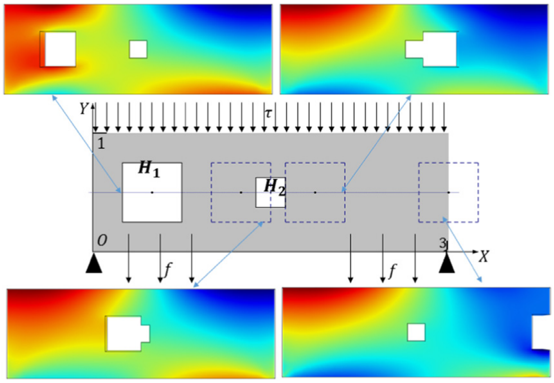

Fig. 1. Direct simulation for a CAD model undergoing parametric modification. The simulation results are given rapidly and directly as hole H_1 moves from left to right.

design space. However, such technologies have various intrinsic limitations. The first lies in the well-known *curse of dimensionality*. Consider for example, a design space with ten design variables, each sampled 10 times. The total number of samples in the space is 10^{10}, whose associated engineering analysis solutions are far too many to compute. For example, Kim et al. [8], used several thousand CPU-hours to perform a limited exploration of the space of detailed clothing effects on a character. Moreover, the size of the simulated results was very large: tens of gigabytes of raw data. Secondly, as the physical space is discretely sampled, it is quite possible that some key physical phenomenon may not be captured by the sampling process. Thirdly, the original physical space may be very complex and intrinsically nonlinear, so approximating it using a linear space will either lose accuracy or require a large basis set. Fourthly, even after deriving the bases, computing approximations to the original problem still requires the solution of a large system of equations, which although smaller or simpler than the original problem, still takes time. Finally, we note that traditional model reduction approaches generally only work for shapes without topological changes, whereas our approach can handle such changes.

Instead, here we give a novel approach for direct simulation for CAD models undergoing parametric modifications. This is achieved by computing *offline* a generic solution as a function of the *design modification parameters*. For example, the physical solution to the model in Fig. 1 is computed as a function in terms of the translation parameter p (as well as x, y, z spatial coordinates). As hole H_1 moves in the x-direction to some new parameter values $p^1, p^2, \ldots$, the physical solution for the modified model can be easily and cheaply derived *online* by evaluating the generic parametric function for the parameter values $p^1, p^2, \ldots$. Note particularly that this solution expression is very different from the conventional FE analysis process which only gives a simulation solution in terms of the spatial coordinates, without the additional parametric dimension. Thus, conventionally, each time the design's geometry is modified, the overall CAD–CAE integration process has to be re-performed, which is very computationally expensive.

This approach is enabled by use of a newly introduced model reduction technique, *proper generalized decomposition* or PGD [9], allowing offline parametric solution computation. Unlike the conventional model reduction techniques as mentioned above, PGD is based on the assumption of a separated form for the unknown physical solutions (in terms of both spatial coordinates and the design parameters). It has demonstrated its abilities to deal with high-dimensional problems, and that it can overcome the limitations of classical approaches [10]. Since its first introduction by Ammar and Chinesta [11,12], the PGD method has been applied to various linear and nonlinear engineering problems involving computational rheology [13], the chemical master equation [14], geometrically parameterized heat problems [15], etc. Here, we extend it to direct simulation for parametrically varying CAD models, which may involve topological change. PGD has not previously been applied to this problem.

Changes in the domain during parametric modification pose a big challenge, particularly topological changes. We resolve this issue by using R-functions, implicit functions that can easily represent a solid's interior, boundary and exterior. R-functions were first suggested in Russian by Rvachev in 1963 [16], and popularized by Shapiro [17]. Unlike other functions with this property, for example RBFs (radial basis functions), R-functions have the useful property that they can readily represent Boolean operations between different geometries, and can also incorporate geometric design parameters. They can thus easily describe models undergoing topological changes. Further discussion of R-functions is deferred until Section 4. By using R-functions and characteristic functions, a physical simulation problem originally defined over a set of CAD models generated by parametric variations is now redefined as a high-dimensional problem on a fixed domain. This allows the PGD computation to be readily performed generically.

Chen, Shapiro and Suresh have also considered using R-functions for design optimization with topological changes [18,19]. Our work differs in its use of the PGD approach to permit fast simulation. We also note that [15,20] have also proposed using PGD for fast simulation involving deformed shapes. However, their work assumes that the FE meshes used have the same topology before and after deformation, which is too restrictive to be of use in general design problems.

In summary, this paper proposes a novel approach for direct simulation for CAD models undergoing parametric deformation; we illustrate it in the context of linear elasticity. It is assumed in this paper that the model's Dirichlet boundary conditions are maintained unchanged, or, the fixed boundary is kept unchanged, during the model modification process. It can interactively predict a simulation's physical solution almost immediately after the designer changes the model's design parameters, even for models undergoing topological changes, unlike previous work. This is achieved by computing *offline* a generic solution as a function of the *design modification parameters* based on the *PGD* model reduction technique in combination with R-functions. It overcomes the limitations of previous model reduction approaches, avoiding large and insufficient sampling spaces, inaccurate approximations, additional online equation solutions, and so on. The proposed approach works for varying models whose Dirichlet boundary conditions (or fixed boundaries) do not change. We demonstrate the computational accuracy and efficiency of the proposed approach, and compare it to conventional FE methods using various numerical examples.

The remainder of the paper is arranged as follows. The problem and overall approach to solve it are described in Section 2. The approach to computing the PGD solution for a CAD model undergoing parametric changes is presented in Section 3. The strategy for unifying the computational domain by using a parametric R-function is explained in Section 4. Numeric examples are presented to illustrate the validity and efficiency of our proposed method in Section 5. The paper is finally concluded in Section 6.

2. Problem statement and approach overview

The purpose of our work is to predict the simulation solution of a CAD model in boundary representation (B-rep) as users perform some parametric editing on it, e.g. moving or reshaping some geometric entities or features; see Fig. 1. We use the popular problem of linear elasticity analysis as a concrete example of our approach.