Computer Aided Geometric Design 43 (2016) 53–67

Contents lists available at ScienceDirect

Computer Aided Geometric Design

www.elsevier.com/locate/cagd

Coupling time-varying modal analysis and FEM for real-time cutting simulation of objects with multi-material sub-domains

Chen Yang [a], Shuai Li [a,*], Yu Lan [a], Lili Wang [a], Aimin Hao [a], Hong Qin [b]

[a] *State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, Beijing, China*
[b] *Stony Brook University, Stony Brook, NY, USA*

ARTICLE INFO

Article history:
Available online 17 February 2016

Keywords:
Physical simulation
Multi-domains
Finite element methods
Modal analysis

ABSTRACT

Powerful global modal reduction techniques have received growing recognition towards significant performance gain in physical simulation, yet such numerical methods generally will fail when handling deformation of heterogeneous materials across multiple sub-domains involving cutting simulation. This is because the corresponding topological changes (due to cutting across multiple sub-domains) and/or drastic local deformations tend to invalidate the global subspace techniques. To ameliorate, this paper systematically advocates a novel deformation and arbitrary cutting simulation approach by adaptively integrating FEM-based fully-physical simulation and local deformation's modal reuse into a CUDA-enabled parallel computation framework. This paper's originality hinges upon the maximal reuse of the space–time-varying local modes from prior fully-physical simulations and the adaptively coupling of sub-domain behaviors, which give rise to great improvement of computational complexity while guaranteeing high-fidelity simulation effects. Other key advantages include, being independent of underlying physical models (e.g., either FEM or meshless methods), being flexibly accommodating sub-domains' heterogeneous material distributions, and being accurately responding to local user interactions. During the initialization stage, we partition the object into multiple sub-domains according to its material distributions and/or geometric structures, and respectively employ FEM for physics-based representation/simulation. During the dynamic stage, for each sub-domain, we leverage its local modal reduction in order to project complex deformations onto a low-dimensional subspace. We dynamically determine the sub-domain-specific switch between deformation reconstruction based on modal reuse and FEM-based physical simulation according to the physically-consistent error estimates, and couple all the sub-domains' physical behaviors together by imposing adjacent sub-domains' geometric-continuity constraints. To validate our method, we conduct extensive and quantitative evaluations over comprehensive and well-designed experiments, and all the experimental results have confirmed the advantages of our method in terms of efficiency, accuracy, and unconditional stableness in practical graphics applications.

* Corresponding author.
E-mail address: lishuai@buaa.edu.cn (S. Li).

http://dx.doi.org/10.1016/j.cagd.2016.02.014

1. Introduction and motivation

Real-time physically-realistic simulation has been one of the mainstreams that continues to attract a great deal of research efforts during the last two decades. So far, its widespread use has been enabling many downstream graphics applications such as computer games, virtual reality systems, computer animation, virtual surgery simulators, etc. To faithfully and efficiently simulate the object's physical behaviors of deformation and arbitrary cutting, many fundamental methodologies, ranging from accurate finite element methods (FEM) together with their GPU acceleration (Dick et al., 2011a) to various types of flexible mesh-free methods, have been well devised to accommodate the application-specific requirements.

In principle, except for the mathematically-rigorous and high-precision modeling of the underlying application-specific physics, most state-of-the-art methods are trying to pursue certain effective and flexible numerical approaches to make tradeoffs between physical accuracy and interactive efficiency, wherein global modal reduction based techniques (Barbič and James, 2005; Kim and James, 2009; Krysl et al., 2001) have gained growing momentum in recent years because of their powerful capabilities in significant simplification of computation complexity and still preserving dominant, global physical behaviors. Despite the great success of global modal reduction, when encountering complex heterogeneous objects, the engineering rationale of global modal reduction towards numerical gains tends to fall short in tackling new challenges, which requires material-sensitive physically-accurate modeling, adaptive handling of flexible topological changes, efficient local modal analysis and reuse, and sophisticated computational schemes in a much more intelligent way. In particular, the key technical challenges are highlighted as follows.

First of all, from the perspective of underlying physical modeling and simulation, most of FEM-based global modal reduction methods commonly discretize the physical domain into homogeneous elements. However, when handling complex homogeneous objects, a naively-transplanted way requires a large number of carefully-divided elements to accurately represent all the involved physical states, which gives rise to expensive computation expenses in modal reduction, and what is even worse is that, the above-documented extra efforts may not facilitate the corresponding global modal analysis towards physical realism due to massive elements from various sub-domains. Therefore, it naturally needs a divide-and-rule scheme (Barbič and Zhao, 2011; Kim and James, 2012) to independently model the involved heterogeneous physical domains in an approximated sense.

Second, from the perspective of the efficient utilization of modal analysis, even though global modal reduction methods have natural advantages in reducing computational expenses, its pre-computed modes may not have capabilities to represent any desirable motion outside the deformation subspace spanned by the global modes. Thus, global modal reduction is impossible to handle cutting and heterogeneous deformation because such behaviors naturally fall outside the space delineated by global modal reduction. Moreover, the topological changes due to arbitrary cutting require to frequently recompute the global modes, otherwise it will lead to un-neglected artifacts, which will inevitably diminish the apparent advantages associated with global modal reduction. Therefore, an effective way to conduct local modal analysis and accommodate local modal reuse is urgently needed.

Third, from the perspective of the numerical-computation efficiency and stableness towards practical applications, explicit integration based solvers (Fierz et al., 2012) indeed offer efficiency at the cost of being only conditionally stable, while implicit integration schemes (Allard et al., 2011) provide the assurance of unconditional stability and support large time steps, however, it usually needs to solve large systems of equations. Therefore, to achieve stable and interactive simulation, CUDA-based domain-parallel implicit solvers are urgently needed. Meanwhile, considering that user's interests in different sub-domains are distinct, in practical applications, it is required to simulate sub-domains of more interest with higher precision. And it is significant to effectively integrate spatially-varying FEM-based sub-domains with full-physical simulation capability and local deformation's modal reuse and to guarantee its correctness in physical and geometrical meanings.

To tackle the aforementioned challenges, our central idea is to extend the powerful global modal reduction method to handle efficient deformation and cutting simulation of dynamic models with heterogeneous material distribution. Specifically, this paper resorts to domain-parallelized physical simulation, subspace-independent physical modes reuse, and cross-domain adaptive behavior tight-coupling in a well-concerted CUDA-based parallel computational framework. The salient contributions of this paper include:

- We pioneer a space–time-varying local modal reuse method by introducing a divide-and-conquer scheme and coupling with the currently-available powerful global modal reduction, which enables spatially-varying deformation of different magnitude and arbitrary cutting simulation of heterogeneous object while guaranteeing high-fidelity simulation effects, and is independent of the underlying physical models (i.e., both FEM-based domain discretization and meshless method are supported).
- We propose to adaptively switch between integrating sub-domain-specific FEM-based simulation with full-physics capability and reconstructing deformation based on approximated, prior modal analysis according to the physics-geometry spatial-continuity error estimates. Such flexibility is dictated by sub-domain importance and sub-domain deformation amplitude, which can take full advantages of the accuracy of domain-specific physical simulation and the efficiency of local modal reduction methods.
- We design a CUDA-based parallel implicit integration framework, which supports material-aware and geometric-structure-aware sub-domain partitioning, dynamic evolution of sub-domain-specific deformation subspace and smooth switch between physical simulation and modal deformation for sub-domains. From the perspective of numerical anal-