ABSTRACTS

(Part 2, M-Z)

Arranged in alphabetical order by presenting author
UNSTRUCTURED T-SPLINES WITH MAPPED B-SPLINE BASIS FUNCTIONS OVER EXTRAORDINARY REGIONS FOR ISOGEOMETRIC ANALYSIS

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\textbf{ABSTRACT}

T-splines are initially proposed in (Sederberg \textit{et al.} 2003) and have been widely studied in recent years as one of the important schemes for isogeometric analysis. T-splines possess important properties of local refinements with similar convergence properties to that of NURBS. This talk presents a scheme of unstructured T-splines with extraordinary vertices for both shape design and isogeometric analysis. Basis functions within two-ring of surface patches incident to extraordinary vertices are defined by direct mapping from cubic B-spline basis functions, while basis functions for all other surface patches are defined in a similar way to that of regular T-splines. Compared with unstructured T-splines presented in (Scott \textit{et al.} 2013), the scheme presented in this talk produces surfaces with exact global C2 continuity, except on the outer loop of boundaries of two-ring surface patches where approximate C2 continuity is achieved, while the scheme in (Scott \textit{et al.} 2013) produces global C2 continuity except at extraordinary corner positions and on all boundaries within two-ring surface patches where C1 or G1 continuity is achieved. Compared with mapped B-splines presented in (Yuan and Ma 2014), there is no need to define a global parameterization with the scheme presented in this talk and it can thus be easily applied to any unstructured T-meshes. Examples on both shape modeling and isogeometric analysis based on the new unstructured T-splines are also presented in the talk.

\textbf{REFERENCES}

LOW RANK REPRESENTATIONS FOR ISOGEOMETRIC GALERKIN METHODS

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ABSTRACT

Isogeometric Galerkin-based simulations can be much more demanding with respect to computation costs, when compared to traditional finite element methods, especially in 3D. More precisely, as a result of the increased polynomial degree and the larger supports of the ansatz functions (tensor-product B-splines), we are faced with a, so called, “curse of dimensionality”, that is, an exponential complexity with respect to the spatial dimension of the computational domain. In this talk we propose a way to overcome this problem, by the use of tensor methods. These methods have been explored the last years in the frame of numerical simulations and have proven quite efficient in several fields such as biology, chemistry, signal processing, and so on.

We focus on the formation, storage and further manipulation of isogeometric Galerkin matrices coming from tensor product (B-spline) functions. We show that the use of tensor methods can lead to great improvements to both memory and computation requirements. This is achieved by deducing an approximate representation of the matrices that occur in Galerkin-IGA as sums of a small number of Kronecker products of auxiliary matrices with small size. This representation is obtained by means of a low-rank tensor approximation of certain kernels which appear in the integrands. We will demonstrate that a systematic use of the tensor-product structure in all operations make it possible to achieve a significant speedup in the overall isogeometric simulation pipeline, without compromising the accuracy of the results.

REFERENCES


A HYBRID IGA-FEM MORTAR METHOD AND
APPLICATIONS
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ABSTRACT

The Mortar method [1] is a technique for splitting the computational domain in
subdomains and allows different choices of discretization in each subdomain. The
continuity of the solution across the common interface is enforced by means of
Lagrange multipliers.

We present a hybrid version of the Mortar method that glues any combina-
tion of standard Finite Element and Isogeometric surfaces [2]. No theoretical
background is explored as we focus on the practical aspects that have to be
taken into account: treatment of the IGA boundaries, generation of the common
mesh for integration, choice of the discrete space for the Lagrange Multipliers,
quadrature rules and many others.

The test cases that we propose are non-linear elasticity problems undergo-
ing large deformation on the Mortar interface. The goodness of the solution and
the method in general is ensured with an analysis of the continuity of the
displacement and other quantities of interest such as strains and stresses.

Geometries, formulation of the equations and implementation come from a
real industrial world scenario.

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ON LOCKING-FREE ISOGEOMETRIC ANALYSIS OF
GEOMETRICALLY EXACT THREE-DIMENSIONAL BEAMS

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ABSTRACT

In this work the geometrically exact three-dimensional (3D) beam theory of Reissner [1], and later revisited by Simo [2], has been used as basis for development of a variety of isogeometric large deformation 3D beam elements. Geometrically exact 3D beam theory has no restrictions with respect to size of displacements, rotations and deformations. Ibrahimbegovic [3] has shown that an improved representation of the curved reference geometry significantly increases the accuracy of the results. Whereas earlier studies [3] utilized C0-continuous Lagrange polynomials, we use NURBS shape functions, for approximation of both geometry and displacements. While reduced integration may be used to alleviate transverse shear and membrane locking in standard C0-continuous Lagrange elements this does not automatically extend to isogeometric elements. In this study we investigate how optimal patch-wise numerical quadrature rules [4] may be used to obtain locking-free isogeometric large deformation geometrically exact 3D beams. Several numerical examples serves to illustrate and assess the performance compared to traditional Lagrange interpolated elements.

REFERENCES

ALGEBRAIC MULTIGRID FOR CONSTRAINED LINEAR SYSTEMS

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ABSTRACT

Linear solvers form the core of many numerical simulation software packages. After discretization and (if needed) linearization of a partial differential equation, a large linear system of equations arises. Typically, the system matrix is sparse, i.e. only a limited amount of entries per row differs from zero independently from the size of the system $N$.

As many algorithmic components of a simulation typically scale linearly with respect to $N$, this should also hold for the linear solver. Direct and one-level iterative solvers like the conjugate gradient method however require quadratic to cubic compute time, so for larger simulations the solution of the linear system may become the most time-consuming task.

Algebraic multigrid (AMG) methods [1] provide optimal iterative linear solvers for a wide class of problems, i.e. they show a linear scaling with respect to $N$ in both compute time and memory requirements. They automatically construct a hierarchy of linear systems to adequately deal with the different frequencies of the underlying problem. To this end, a so-called setup phase is carried out before the iteration starts. In plain AMG algorithms, the setup phase only needs the original system matrix as input and further constructs the hierarchy in a mainly black-box manner. However, these methods more or less implicitly assume that their input is a symmetric positive definite, (weakly) diagonally dominant matrix, as it typically arises from finite difference, finite volume or linear finite element discretizations of second order partial differential equations.

In many applications in science and engineering, this matrix structure cannot be assumed. To successfully construct AMG hierarchies for these system, algorithmic modifications to the AMG setup phase are required and additional input (which usually is available in the simulation software anyway) must be delivered to AMG.

In this talk, we describe some of these extensions. In particular, we present strategies to deal with linear systems with constraints. Such constraints for example arise from not eliminated boundary conditions, but we also present an AMG method for saddle point matrices as they occur in coupled velocity-pressure CFD simulations.

(This is joint work with the Grid-free methods group at Fraunhofer ITWM.)

REFERENCES

IMPROVEMENT QUADRATURE RULES FOR REDUCING DISPERSION ERROR IN ISOGEOMETRIC ANALYSIS OF WAVE PROPAGATION PROBLEMS

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ABSTRACT

We study the dispersion analysis of wave propagation problems under the Isogeometric Analysis framework. By blending Gauss-Legendre and Gauss-Lobatto quadrature rules, we prove that the dispersion error of bi-quadratic NURBS can be improved from 4th order accuracy up to 6th order accuracy. This new quadrature rule can be efficiently implemented by replacing the Gauss-Legendre quadrature that used to construct mass matrix and stiffness matrix. Moreover, we take advantage of the high regularity of spline basis functions to improve the efficiency of the quadrature rule. A set of benchmark problems demonstrates that the new quadrature rule for NURBS outperforms that for Lagrange basis functions.
SOLVING COMPRESSIBLE FLOW PROBLEMS

BY ISOGEOOMETRIC ANALYSIS

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ABSTRACT

Since its introduction in [3] IgA gained popularity in many computational mechanics and fluid dynamics applications but its use in compressible flow calculations is very limited.

In this paper, we present our implementation of a positivity-preserving isogeometric high-resolution scheme for compressible flow problems in the open-source library G+Smo [4]. It builds upon the generalization of the algebraic flux correction paradigm [5] to multi-patch IgA as universal building block for the design of positivity-preserving high-order discretizations. In particular, we analyze techniques for the positivity-preserving multi-patch coupling and boundary treatment.

Our implementation adopts Fletcher's group formulation [1] together with an efficient edge-based formation of system matrices and vectors [2] from pre-computed coefficients to overcome the high computational costs that are typically observed in quadrature-based IgA-assembly algorithms.

REFERENCES


GENERATING LOW RANK SPLINE SURFACES FROM BOUNDARY CURVES

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ABSTRACT

It has been observed recently that for tensor-product spline surfaces with low rank coefficients a significant speed-up in isogeometric matrix assembly can be achieved [1]. Indeed, one may exploit the low rank structure and efficiently perform multivariate integration by reducing it to a sequence of univariate quadrature operations, thus counteracting the well-known curse of dimension. Therefore, we are interested in understanding when do spline surfaces possess coefficients with low rank and, in particular, how to construct such surfaces from given boundary curves.

First, we reconsider the classical constructions such as Coons surfaces [2]. We analyze the rank of the resulting parameterizations. Then, we propose a new coordinate-wise rank-2 interpolation algorithm and discuss its extension to the case of parametric boundary curves in \(d\)-dimensional Euclidean space. We discuss further properties of the new construction, which include the permanence principle and reproduction of bilinear surfaces. Special attention is paid to the property of affine invariance. Finally, we also show that the ranks of the resulting surfaces are lower than those of surfaces created by Coons interpolation or other methods, thus making them more suitable for isogeometric analysis with a low rank matrix assembly.

REFERENCES


LOCAL REFINEMENT FOR T-SPLINES IN ANY DIMENSION

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ABSTRACT

T-splines are a generalization of tensor-product B-splines to non-uniform meshes. They have been introduced as a free-form geometric technology in the Computer-Aided Design community and have therefore caught much attention in Isogeometric Analysis, particularly with regard to constructing an Adaptive Finite Element Method that directly uses data structures from CAD applications.

We present a generalized adaptive refinement procedure for n-dimensional axis-parallel box meshes with user-defined grading, i.e., the user chooses the number of children in a single elements' refinement. We prove linear independence of the T-spline functions that correspond to the generated meshes, nestedness of the generated T-spline spaces and linear computational complexity of the refinement procedure in terms of the number of marked and generated mesh elements.
SMALL AND LARGE DEFORMATION ANALYSIS WITH MATERIAL POINT METHOD WITHIN THE ISOGEOMETRIC FRAMEWORK

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ABSTRACT

The material point method (MPM) is a version of the particle-in-cell (PIC) which has substantial advantages over pure Lagrangian or Eulerian methods in numerical simulations of problems involving large deformations. Using MPM helps to avoid mesh distortion and tangling problems related to Lagrangian methods and the advection errors associated with Eulerian methods are also avoided. Despite the MPM being promoted for its ability to solve large deformation problems it suffers from instabilities when material points cross between elements. These instabilities are due to the lack of smoothness of the grid basis functions used for mapping information between the material points and the background grid. By introducing a weighting function with higher degree of smoothness, the generalized interpolation material point (GIMP) method is capable of reducing these errors and improving accuracy. Convected particle domain interpolation (CPDI) is another algorithm developed to improve the accuracy and efficiency of the material point method for problems involving extremely large tensile deformation and rotation. However, both methods require the basis functions (normally taken to be linear) to be integrated over the domain of the material point of interest, they also do not fully eliminate spurious oscillations due to cell crossing. In this paper a novel high-order material point method within an isogeometric analysis (IGA) framework is developed. Utilizing high-order basis functions enables more accurate determination of physical state variables e.g. stress. The smooth spline function spaces are used to eliminate the cell-crossing instability.

REFERENCES

A NEW IMMERSED ISOGEOMETRIC-MESHFREE TECHNIQUE FOR FLUID-STRUCTURE INTERACTION PROBLEMS INVOLVING HIGH MACH NUMBERS

PART II

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ABSTRACT

Fluid-Structure Interaction for high Mach number flows, such as blast loading on structures, is a highly complicated and challenging problem. Its accurate numerical simulation requires a robust fluid solver for the compressible Navier-Stokes equations, an advanced computational method that can capture possible disintegration of the structure, as well as a sophisticated fluid-structure interaction (FSI) technique. Part I of this work presents a stabilized formulation for the solution of the compressible Navier-Stokes equations. The resulting weak form is discretized using Non-Uniform Rational B-Splines (NURBS) in space, and is therefore a higher order method. An explicit second-order accurate time integration scheme is employed to advance the equations in time. Numerical examples of high Mach number flows are presented. Part II presents the structural discretization and the adopted FSI technique. Solids subjected to blast exhibit excessive material distortion, therefore a reproducing kernel particle method (RKPM) is proposed for the structural discretization. This technique alleviates possible mesh distortion difficulties associated with Lagrangian Finite Element Methods. The adopted FSI technique originates from the Immersed Finite Element Method. A fixed background Eulerian mesh is used for the Fluid, while Lagrangian meshfree solid particles move on the top of the background grid. Following the methodology presented in Part I, the background grid is discretized with NURBS in space and with an explicit second order method in time. Both fluid and structural quantities are solved on the background grid. Exchange of information between fluid and structure is achieved through a higher order interpolation function. FSI examples of structures subjected to blast are presented.
AN EXTENDED ISOGEOGMETRIC ANALYSIS BASED ON PHT-SPLINES FOR CRACK PROPAGATION

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ABSTRACT

In this work, an extended isogeometric analysis based on polynomial splines over hierarchical T-meshes (PHT-splines) is applied to study crack growth of the inclusion-crack interactions in an elastic medium. The PHT-splines overcome some shortcomings of non-uniform rational B-splines based formulations; in particular, they allow for adaptive h-refinement with ease. In order to drive the adaptive refinement, we present a recovery-based error estimator for this approach. The signed distance function and orthotropic crack tip enrichment functions are adopted for extrinsically enriching the conventional isogeometric analysis approximation for representation of strong discontinuity and reproducing the stress singular field around a crack tip. The crack faces are modeled by discontinuous Heaviside function, while the stress singularity at the crack tip is modeled by crack tip enrichment functions. The holes and inclusions are modeled by the Heaviside function and distance function, respectively. The influence of the crack length, and the number geometry of the inclusions on the crack tip stress field are numerically studied. The interaction integral for homogeneous materials is used to compute the stress intensity factors of the crack tip. The convergence, accuracy, and stability of the method in the solution of two-dimensional elasto-static problems are compared with those of other methods available in the literature, showing improved accuracy.

REFERENCES


ALGEBRAIC MULTIGRID FOR PARTICLE-BASED AND MESHFREE METHODS

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ABSTRACT

For a software tool to be accepted by its users, it needs to be robust and fast. Many software tools using particle-based or other meshfree methods spend most of the runtime in their linear solvers. For large numbers of particles, direct solvers on the one hand become expensive both in terms of runtime and memory requirements. On the other hand, classical iterative solvers often suffer from poor convergence or even divergence, leading to long runtimes and less robustness. In order to keep runtime and memory requirements acceptable while also preserving robustness, we have extended the linear solver library SAMG [1], which is based on Algebraic Multigrid Methods (AMG) [2], to particle-based and meshfree applications. AMG is a class of iterative solvers that construct a hierarchy of smaller linear systems based only on the matrix of the original linear system. Hence, AMG-solvers consist of two phases: a setup phase, where the hierarchy is automatically constructed, and a solving phase. Since AMG was originally developed with mesh-based applications in mind, we needed to adjust both phases to the problems posed by particle-based methods. As a result we were able to run simulations that either were not possible before – due to divergence in the classical iterative method used before – or took prohibitively long to run. Especially when increasing the number of particles in a given model, thus increasing the accuracy of the simulation, the overall runtime benefits from AMG's optimal O(n) – n being the number of particles – scaling behavior compared to other iterative methods. We have validated our work with different industrial applications varying in problem size and complexity. Those applications vary for example in the number of phases being modeled, the approach to discretize the Navier-Stokes equations, the Reynold's number of the fluid and the complexity of the underlying geometry. In addition to that, the code we have developed is both OpenMP- and MPI-parallel. In conclusion, the tool we have created by integrating AMG into the existing software can now handle a wider range of applications and delivers results faster than before. This is joint work with the Grid-free Methods group at Fraunhofer ITWM.

REFERENCES

PRECONDITIONING THE ENRICHED CONFORMAL DECOMPOSITION FINITE ELEMENT METHOD FOR MULTIPHASE AND MULTIMATERIAL PROBLEMS

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ABSTRACT

Enriched finite element methods such as the Generalized Finite Element Method (GFEM), the eXtended Finite Element Method (XFEM), the Hierarchical Interface Enriched Finite Element Method (HIFEM) and the Conformal Decomposition Finite Element Methods (CDFEM) are powerful tools for multiphase and multimaterial problems. These methods provide discretizations that dynamically adapt to the moving material and phases to accurately capture the interfacial physics and discontinuities. In order to allow for a discontinuous description across interfaces, these methods introduce some type of enrichment in the elements that are crossed by these interfaces. Additional unknowns are assigned to one or more of the mesh entities (elements, nodes, sides, or edges) that are associated with these interfacial elements, and additional equations are formulated for these unknowns.

The Conformal Decomposition Finite Element Method (CDFEM) is an enriched finite element method that can be used to describe arbitrarily discontinuous physics across dynamic interfaces. Level sets are used to describe the location of the moving interfaces. Nodes are added at the intersection of the level set surfaces with the edges of the input mesh, and a conforming mesh is generated automatically. Standard unstructured mesh data structures are generated for the resulting conformal mesh in terms of element blocks and side sets. This general framework allows the physics code to describe either weak or strong discontinuities across the interfaces using standard finite element methods.

CDFEM been used at Sandia to address several complex multiphase and multimaterial problems including pore scale modeling of laser welding, electrochemical battery response, the thermal degradation of organic materials, and the conductive burn of energetic material in a confined domain. Several issues arise in the development of robust enriched finite element methods for realistically complex transport problems. These issues include boundary conditions, time stepping, and poor conditioning of the enriched system of equations.

In this talk, a new method for preconditioning the enriched system of equations that are obtained using CDFEM is presented. The method is shown to produce well-conditioned systems of equations regardless of the interface location. Previous work either used expensive general-purpose solvers or modified CDFEM to eliminate the small angle conformal elements. These techniques, however, are not applicable for large scale parallel problems with many, complex interfaces and boundaries. By noting the relationship between CDFEM and hierarchical enrichment, a relatively simple change of variables can be used to recast the system of equations into one that is easily preconditioned using simple Jacobi preconditioners. Verification results will be presented that show that optimal rates of convergence in space and time are obtained for all test problems.

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.
IGA IMPLEMENTATION FOR SOLIDS IN RADIOSS

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ABSTRACT

Isogeometric analysis has shown to be a very promising tool for an integrated design and analysis process [1]. A challenging task is still to move IGA from a proof of concept to a convenient design tool for industry and this work contributes to this endeavour. This communication deals with the implementation of IGA concept into Radioss explicit code in order to address crash and stamping simulation applications.

To this end, the necessary ingredients to a smooth integration of IGA in a traditional finite element code have been identified and adapted to the existing code architecture. First, a solid NURBS element has been developed in Radioss and then, an existing contact interface has been extended in order to work seamlessly with both NURBS and Lagrange finite elements. Some academic and simple industrial cases will be presented to show the obtained results and the relevance of the retained solution.

Mesh refinement is the third ingredient added to this integration. As local refinement is needed for solution approximation and for patch connection, we implemented two approaches: truncated hierarchical B-Splines (THBS) [3] and locally refined B-Splines (LRBS) [4]. A comparison of the two approaches is made in terms of additional data requirements and implementation aspects. Obtained results with both techniques will be displayed and discussed.

REFERENCES


THE ULTIMATE IGA SPACE FOR TURBULENT INCOMPRESSIBLE FLOW?
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**ABSTRACT**
Since its early days, the benefits of IGA spaces for incompressible flow have been recognized, and different approaches have been investigated. We mention three important classes: Stabilized equal-order. These simple but effective interpolations have been successfully applied to turbulent flow [1,2], showing a high per-degree-of-freedom accuracy and benefits of weakly enforcing no-slip conditions. Divergence-compatible. A both elegant and important alternative is embodied in the extension of the Raviart-Thomas element to IGA, which satisfies the divergence constraint in a pointwise sense. This space was put forward in [5]. Inf-sup stability, conservation properties as well as extensions to, e.g. the multi-patch case, was performed in [6]. A mesh-adaptive extension was presented in [7], and a framework for Variational Multiscale turbulence modeling discussed in [8].
IGA Taylor-Hood. Extension of these classical elements to IGA have been made in [3]. We also mention the Subgrid element of [4]. Inf-sup stability is retained, even when essential boundary conditions are imposed strongly. In contrast to the previous two classes, the errors in the velocity and pressure are balanced. Taylor-Hood elements are known for underconstraining the velocity space. Although they satisfy an inf-sup condition, stability deteriorates in the convection-dominated regime. The size of the velocity space also leads to larger problem sizes compared to the other alternatives. On the other hand, the first two approaches have velocity interpolants which converge slowly. Observing the advantages of both high-continuity [1] and weakly-enforced wall conditions [2] for turbulent flow, we see an opportunity to unite most of the advantages of the above-mentioned classes in what we have dubbed the “full-regularity Taylod-Hood” element: an inf-sup stable element (provided weak enforcement at essential boundaries) with balanced errors, enhanced stability in the convection-dominated regime (w.r.t. Taylor-Hood), and problem sizes comparable to equal-order and div-compatible approximations.
We investigate stability in both the diffusion- and convection-dominated regimes, offer a trade-off between exact conservation properties and velocity error convergence rates and investigate in which cases which approximation space is ideal.

**REFERENCES**
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A GENERAL-PURPOSE MESH GENERATION METHOD FOR FLUID MECHANICS COMPUTATIONS WITH THE IGA

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ABSTRACT

Methods with key components that include the Space–Time Isogeometric Analysis (ST-IGA) [1, 2] are being used increasingly in fluid mechanics computations with complex geometries. In such computations, the ST-IGA complements the ST Variational Multiscale (ST-VMS) method [3, 4], which serves at the core method, sometimes together with other key components, such as the ST Slip Interface (ST-SI) method [5]. To make the ST-IGA use, and in a more general context the IGA use, more practical in fluid mechanics computations, NURBS volume mesh generation needs to be easier and as automated as possible. To that end, we present a general-purpose NURBS mesh generation method. The method is based on multi-block structured mesh generation with existing techniques, projection of that mesh to a NURBS mesh, and recovery of the original model surfaces. It is expected to retain the refinement distribution and element quality of the multi-block structured mesh that we start with. The flexibility of discretization with the general-purpose mesh generation is supplemented with the ST-SI method, which allows, without loss of accuracy, C¹ continuity between NURBS patches and thus removes the matching requirement between the patches. We present a test computation for the turbine part of a turbocharger, which demonstrates that the general-purpose mesh generation method proposed makes the IGA use in fluid mechanics computations more practical.

REFERENCES


A MULTI-TIME-STEP METHOD FOR PARTITIONED TIME INTEGRATION OF PERIDYNAMICS

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ABSTRACT

Peridynamics is a nonlocal reformulation of continuum mechanics that is suitable for representing deformations with discontinuities, see [1, 2] and the references therein. We extend the peridynamic formulation to allow the use of multiple time steps within a single problem domain by decomposing that domain into a number of smaller subdomains, where the critical regions of interest are solved using a small time step and the rest of the problem domain is solved using a larger time step. We explore the numerical properties and computational cost of the proposed approach, and demonstrate through numerical examples that a multi-time-step discretization of peridynamics can be solved much faster than a uniform time step discretization, and without adversely affecting the accuracy of the computed solution [3].

REFERENCES


COUPLED LAGRANGIAN AND SEMI-LAGRANGIAN RKPM

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ABSTRACT

In a RKPM Meshfree-type discretization, approximation is achieved through construction of the shape functions in the physical domain and the interaction of neighboring nodes. When modeling deformation problems, a Lagrangian [1, 2] and a semi-Lagrangian formulations [3, 4] have been proposed, where the reproducing kernel (RK) functions are evaluated in the reference initial coordinates and the current configuration, respectively. In the RKPM Lagrangian meshfree formulation the variational equations are formulated in the undeformed configuration, and the RK functions and their derivatives are thus evaluated in the undeformed configuration. However, the Lagrangian RKPM breaks down when the deformation gradient loses positive definiteness, such as in modeling high velocity impact and penetration processes. The semi-Lagrangian RKPM formulation with RK functions evaluated in the current configuration eliminates the requirement on the deformation mapping but results in a high computational cost. In order to retain the advantages of both formulations, this work proposes temporal and spatial coupling schemes to allow transition from Lagrangian to semi-Lagrangian RKPM meshfree formulation. In this work, the basic Lagrangian and semi-Lagrangian Meshfree approaches are reviewed, the proposed coupling scheme is presented, and its performance is verified through a suite of benchmark problems.

REFERENCES


ADAPTIVE FEM-BASED NONRIGID IMAGE REGISTRATION USING TRUNCATED HIERARCHICAL B-SPLINES

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ABSTRACT

The current challenges for image registration methods involve performing image registration with large-scale deformations in the most efficient way possible in terms of accuracy and computational cost. The proposed approach involves a new efficient way to solve FEM-based image registration problems using local refinement and Truncated Hierarchical B-spline (THB-spline) basis functions. Large deformation regions are detected and locally refined capturing both large and highly localized deformations efficiently without introducing too many control points. In addition, THB-spline basis functions improve the sparsity of the matrices and satisfy partition of unity, which is desirable for FEM-based computation. This improves efficiency of the registration as compared to uniform subdivision. The proposed method is tested on 2D synthetic and medical images to demonstrate its effectiveness.

Keywords: Nonrigid image registration, Truncated hierarchical B-splines, Adaptive local refinement, Finite Element Method

REFERENCES

A LOCAL KINEMATIC/KINETIC COUPLING ALGORITHM FOR NON-MATCHING ISOGEOMETRIC/FINITE ELEMENT DISCRETIZATIONS

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The purpose of this talk is to discuss a new algorithm for coupling non-matching geometries in computational fluid structure interaction. This method was developed with the idea of integrating existing technologies in a way that incorporates the best of both worlds, specifically between Iso-Geometric Analysis (IGA) and Finite Element Methods/Finite Volume Methods (FEM/FVM). IGA, a simulation methodology in which computer aided design (CAD) technologies are directly integrated into finite element analysis, is ideally suited for dealing with structures because the availability of smooth, higher order basis functions allow for accurate solutions with far fewer degrees of freedom. Meanwhile, FEM/FVM methods are better suited for fluids as stable and efficient numerical schemes may be constructed for unstructured tetrahedral meshes. By meshing the local Bezier elements of the structure into triangles, a simple algorithm can be defined that maps the surface tractions of the fluid tetrahedrals to the surface of the structure and structural displacements to the wetted fluid surface. The only requirement is that the triangles must respect the boundaries of the Bezier elements. The resulting algorithm is computationally efficient, higher-order accurate, and easy to implement.
DESIGN AND ANALYSIS FOR IRREGULAR PATCH LAYOUT

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ABSTRACT

Tensor-product splines are the preferred representation of smooth parametric surfaces in computer aided design. At irregularities, where less or more than four splines join, special constructions are needed to achieve smoothness. According to [1], $G^k$ constructions automatically yield $C^k$-continuous isogeometric elements: [4, 2, 5]). Have shown this approach to be effective on the standard FEM obstacle course. However, exact multi-resolution of $G^k$ surfaces is non-trivial. Several alternative constructions with nested refinement, such as [6] will be discussed.

REFERENCES

MODELLING DELAMINATION IN COMPOSITES USING THE ISOGEOGRAPHIC ROTATION-FREE SHELL FORMULATION

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ABSTRACT

Numerical simulations have become fundamental for the design and the analysis of composite structures. However, several difficulties arise due to the complex damage mechanisms of laminated composites. An accurate representation of the damage modes, combined with an efficient numerical formulation, is therefore crucial in order to simulate the behavior of large scale composite laminates from the elastic range to the failure point.

A multi-layered shell modelling approach is developed in the framework of the isogeometric analysis (IGA) based on a higher-order accurate and higher-order continuous non-uniform rational B-splines (NURBS) [1], that allow to adopt a computational efficient rotation-free shell formulation [2,3]. The IGA provides distinct benefits over traditional finite element analyses (FEA), which include: 1. More accurate than traditional FEA, CAD-like representation of the structure’s geometry; 2. Higher-order-accurate representation of stresses, which “drive” the inter-lamina damage modes [4]; 3. Enhanced numerical robustness with respect to mesh distortion [5]. The laminate is modelled at the lamina level, while the intra-laminar damage modes, such as delamination and matrix cracking due to transverse shear stress, are modelled by connecting the composite layers through cohesive interfaces governed by local traction-separation laws.

The model is validated through the correlation with experimental data obtained from low velocity impact tests. The smoothness of the NURBS discretization is shown to be beneficial for the penalty formulations adopted both for the cohesive interfaces and the contact interactions. It is found that, with the proposed IGA approach, issues that typically affect impact problems, such as through-thickness element distortion/inversion which may cause accuracy loss, shortening of time steps, and numerical instability/crashing of the code, are often circumvented.

REFERENCES

METHOD OF DIMENSIONALITY REDUCTION (MDR) IN CONTACT MECHANICS: SIMULATION OF NORMAL AND TANGENTIAL CONTACTS, ADHESION AND CONTACT WITH GRADED MATERIALS

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In the present talk, an overview of the Method of Dimensionality Reduction (MDR) will be presented. MDR is a new method of simulation of contact and frictional forces between elastic and viscoelastic solids [1]. Numerical implementation of MDR allows to integrate the direct simulation of frictional contacts in finite elements or multi-body programs.

The MDR is based on the observation that close analogies exist between certain types of three-dimensional contact problems and the simplest contacts with a one-dimensional elastic foundation. Thereby, it is important to emphasize that this is not an approximation: The properties of one-dimensional systems coincide exactly with those of the original three-dimensional system, if the form of the bodies is modified and the elements of the foundation are defined according to the rules of the MDR.

At the present type, MDR can be applied to many classes of contacts including normal, tangential contact, contacts with elastomers and adhesive contacts. Initially, the MDR has been developed to map simply connected contacts. Recently, it has been extended also for multiple-connected contact problems as e.g. a contact with a toroidal indenter or a rough surface [2].

The newest developments of the MDR in application to Functionally Graded Materials will also be presented [3].

All the necessary mapping rules are presented and their ease of use explained by solving contact problems based on actual examples and up to now unsolved problems.

Possibilities of combining the MDR approach with FE and mesh free programs are discussed.

REFERENCES
VARIATIONALLY CONSISTENT COUPLING OF NON-MATCHING FINITE-ELEMENT AND MESHFREE DISCRETIZATIONS

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ABSTRACT

Numerical analysis of large-scale problems in structural mechanics that span multiple scales of response usually requires very fine spatial and temporal discretization. However, using a uniformly small size of time-step and fine mesh/discretization for the entire domain is computationally very expensive. Domain decomposition is an approach that allows one to reduce this computational cost by dividing the structure into smaller subdomains and using different levels and types of discretizations for different subdomains. However, various numerical issues arise in the process of coupling these subdomains back and enforcing continuity across the interfaces to obtain the global solution. By using different types of discretizations, such as meshfree methods and finite element methods, or by using different levels of finite element mesh refinement in adjacent subdomains, non-matching interfaces are created. Models containing such non-matching interfaces are in general not able to pass basic patch test due to inconsistencies in the numerical integration across these interfaces.

In this study, a variationally consistent coupling (VCC) method is developed to ensure that basic patch tests are passed by models containing non-matching interfaces for any choice of numerical integration over the interface. In addition to non-matching meshes in space, the use of different time steps in different subdomains can also lead to problems. A simplified multi-time-step coupling method for non-linear problems is presented which possesses improved computational efficiency over the conventional consistent multi-time-step method. Numerical examples investigating both these aspects domain decomposition, spatial and temporal, are presented to study the performance of the proposed methods and to study the effect of the presence of these numerical interfaces in such coupled models.

REFERENCES

We present an approach for isogeometric analysis of 3D objects using rational Bezier tetrahedral elements. In this approach, both the geometry and the physical field are represented by trivariate splines in Bernstein Bezier form over the tetrahedral triangulation of a 3D geometry. Given a NURBS represented geometry, either untrimmed or trimmed, we first convert it to a watertight geometry represented by rational triangular Bezier splines (rTBS) [1]. For trimmed geometries, a compatible subdivision scheme is developed to guarantee the watertightness. The rTBS geometry preserves exactly the original NURBS surfaces except for an interface layer between trimmed surfaces where controlled approximation occurs. From the watertight rTBS geometry, a Bezier tetrahedral partition is generated automatically. By imposing continuity constraints on Bezier ordinates of the elements, we obtain a set of global $C^r$ smooth basis functions and use it as the basis for analysis. Numerical examples demonstrate that our method achieves optimal convergence [2] in $C^r$ spaces and can handle complicated geometries.

REFERENCES


REGULARITY OF SOLUTIONS FOR NONLOCAL SYSTEMS

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ABSTRACT

The emergence of nonlocal theories as promising models in different areas of science (continuum mechanics, biology, image processing) has led the mathematical community to conduct numerous and varied investigations of systems of integro-differential equations. In this talk I will present some recent results on regularity of solutions to integral equations with weakly singular kernels. This work is part of a developing theory that is the nonlocal counterpart of elliptic regularity; indeed, many nonlocal results mimic well-known properties and theorems that hold for elliptic systems. The implications could have far-reaching applications in mathematics, at both theoretical and applied levels.

REFERENCES

THE FINITE CELL METHOD FOR COUPLED AND MULTISCALE PROBLEMS – APPLICATION TO ADDITIVE MANUFACTURING

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ABSTRACT

Fictitious domain or immersed boundary methods embed a domain of computation into a larger, usually simply shaped region, which can easily be discretized in a grid of simple square or cubic cells. These cells are not aligned to the boundaries of the original domain, i.e. they do not follow one of the central requirements of finite element meshes. In this sense fictitious domain method are meshfree. Whereas first, low order fictitious domain methods date back to the 1960ies, high order fictitious domain methods like the Finite Cell Method (FCM) have come into the focus in combination with p-version shape functions \cite{1} or Isogeometric Analysis \cite{2} more recently. They combine high accuracy and efficiency with large geometric flexibility, and for a p-extension applied to smooth problems, even exponential rate of convergence could be proven \cite{3}. In case of multiscale problems, however, locally enriched approximation spaces are necessary. We demonstrate in this paper the application of a transient, hierarchical enrichment \cite{4} to Selective Laser Melting (SLM), a highly successful additive manufacturing process. In this thermo-mechanically coupled problem large scale differences need to be bridged, as the local energy input and the phase change from powder via fluid to solid is induced by a laser beam with a focus orders of magnitude smaller that the workpiece. Its meshfree nature renders the FCM particularly suitable for this problem type, as no remeshing is necessary to follow the laser beam with its solidification front.

REFERENCES


ISOGEOOMETRIC COLLOCATION: RESULTS, APPLICATIONS, AND OPEN PROBLEMS

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ABSTRACT

Isogeometric analysis (IGA) was introduced in [1] with the main aim of bridging Computer Aided Design (CAD) and Finite Element Analysis (FEA). In addition, thanks to the high-regularity properties of its basis functions, IGA showed a better accuracy per-degree-of-freedom and an enhanced robustness with respect to standard FEA. However, a well-known important issue of IGA is related to the development of efficient integration rules able to reduce the high array formation costs induced by standard Gaussian quadrature, in particular for higher-order approximations.

In an attempt to address the issue above taking full advantage of the special possibilities offered by IGA and in particular by the available higher regularity, isogeometric collocation (IGA-C) schemes have been first proposed in [2]. The main idea of IGA-C consists of the discretization of the governing partial differential equations in strong form, within the isoparametric paradigm, reducing the number of evaluations needed for array formation to only one per degree of freedom. The aim is to optimize the computational cost still relying on IGA geometrical flexibility and accuracy. In general, IGA-C features look particularly attractive when evaluation and formation costs are dominant, as in the case, e.g., of explicit structural dynamics. Detailed comparisons with both IGA and FEA Galerkin-based approaches were carried out, showing IGA-C advantages in terms of accuracy versus computational cost, in particular for higher-order approximation degrees.

Since its introduction, many promising significant works on IGA-C were published in different fields, including, among others, phase-field modeling, linear and nonlinear elasticity, contact, as well as several interesting studies in the context of structural elements (see, e.g., [3] and references therein).

In particular, IGA-C allows to reach new frontiers for mixed formulations, where methods that are known to be unstable in the Galerkin framework seem to be stable and very efficient when recast in the context of IGA-C.

Finally, it has been recently shown that IGA-C can be conveniently combined with many different spline spaces, able for example to be locally refinable or possessing other desirable properties not available with classical B-splines or NURBS (like, e.g., Hierarchical NURBS, T-splines, or Generalized B-splines).

All these results naturally propose collocation as one of the most promising research directions in the field of IGA, able to combine simplicity and efficiency with an incredibly high potential. In this talk, a review of IGA-C results, applications, and open problems will be given.

REFERENCES


AN INTERACTIVE ADAPTIVE FEM/MESHFREE COUPLING APPROACH FOR THE DUCTILE FRACTURE SIMULATION IN 3D SOLID

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ABSTRACT

The ductile fracture process experiences two phases: the strain localization phase as a consequence of the growth of micro structure defects and the material separation phase as the result of the macro crack propagation. The numerical simulation of the first phase suffers from the pathological localization deformation, i.e., the mesh sensitivity. The numerical challenge for the second phase lies on the sophisticated book-keeping algorithm to trace the evolving crack surfaces, especially in the 3D cases. This work starts with a simulation using FEM mesh. A finite element will alternate into a group of meshfree particles providing the sub-scale information needed when the strain localization emerges. To regularize the non-unique solution in the sub-scale meshfree computation domain, a strain morphed nonlocal meshfree theory is adopted which consists of an nonlocal gradient type of stabilization strain term and an integral type of nonlocal morphed damage model. A phenomenological-based intrinsic material length scale is introduced through this interactive adaptive procedure to respect the fracture energy dissipated in the micro defects growth. Finally, the degradation of solid results in the macro crack initiation and propagation. A special attention is payed to discretize the continuous crack surface by an element wise discontinuous surfels. Each surfel cuts through the whole group of meshfree particle inside one original finite element basing on the characteristic damage distribution of these particles. Several numerical benchmark tests are conducted to demonstrate the convergence and accuracy of the proposed approach for ductile fracture analysis.

Keywords: FEM/Meshfree, nonlocal, stabilization, regularization, surfel

REFERENCES


USING A COMMON GEOMETRY DESCRIPTION TO ENABLE OPTIMIZATION-BASED DESIGN

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ABSTRACT

Solid modeling software and simulation software use fundamentally different geometric representations. In a typical design/analysis workflow, the model is constructed in a CAD package using a surface-based representation and then converted into a discrete volume-based representation that can be used during the simulation phase. This is the meshing process. Decades of research have gone into developing viable tools for this ‘conversion’, but meshing of complicated models continues to pose a considerable challenge. The impact of this incompatibility in geometric descriptions is compounded when optimization-based design tools are used. During optimization-based design, i.e., shape, topology, material optimization (STMO), parts of the design are computed or modified as a field on the volume-based representation. If the designer wishes to modify the computed design or incorporate the design into an assembly, the model must be converted back to a surface-based solid model that traditional CAD packages can manipulate. Considerable effort has been invested in developing this capability, and currently no robust, general-use solution exists.

To enable modeling and simulation of complex parts and assemblies, and to fully integrate simulation into the design process, modeling and simulation must use the same underlying geometric description. An effort is underway to unify modeling operations and simulation/STMO operations by creating a universal volume-based geometric description. This solution consists of a nonconformal background discretization and a collection of level set functions that accurately defines the system shape, topology, and material on the background discretization. To this end, the Generalized Finite Element Method (GFEM[1]) has been implemented in Albany[2] and integrated with the existing topology optimization capability. This talk will i) present the details of this approach in the context of combined shape and topology optimization, ii) describe the implementation in Albany, and iii) present example applications to demonstrate the approach.

REFERENCES


*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
APPLICATION OF MESHFREE METHODS TO PENETRATION AND BLAST EFFECTS MODELING

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ABSTRACT

Material and structure response to extreme events like explosive detonation and projectile penetration is an area of significant interest to the engineering and scientific communities. The analysis of system response necessitates robust methods to accurately model complex target and penetrator failure mechanisms that occur as the result of the extremely high-rate, impulsive loading. The ability to accurately model this complex behavior is critical for reliable analysis and design, and yet presents unique challenges for the development of accurate and robust numerical techniques. The actively developing class of meshfree methods provides new capabilities in this field by naturally capturing large deformation and material separation without nonphysical treatments required by other approaches. To advance computational capabilities for modeling extreme events, new methods like the Reproducing Kernel Particle Method (RKPM) [1] and enhancements of the Generalized Particle Algorithm [2] have been developed and implemented in Lagrangian penetration and blast codes. For RKPM, a stabilized semi-Lagrangian formulation is utilized for accurate numerical integration in the presence of material fragmentation, and evolutionary contact conditions between target and penetrator are addressed through a contact algorithm that obviates the need for a priori contact surface definitions. Penetration into concrete is of specific interest, so improved constitutive descriptions like a multiscale material damage model [3] that links continuum-scale damage with microstructure fracture are also implemented. Projectile penetration and blast loading simulations are presented and compared to experimental data for validation of the formulations’ accuracy when modeling these type of extreme events.

Permission to publish was granted by Director, Geotechnical and Structures Laboratory.

REFERENCES


A PHASE-FIELD FRACTURE MODEL FOR ANISOTROPIC SHELLS

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ABSTRACT

Phase-field descriptions for fracture recently gained much attention avoiding any tracking of the discontinuous fracture zone or material interfaces. Furthermore, exploiting the surface description of thin shell formulations the computational complexity proves a reasonable efficiency even for three-dimensional structural designs.

In this talk we apply a phase-field fracture model to NURBS-modeled shell structures [1] and highlight new aspects with regard to the anisotropy of composite material models, material interfaces and model refinement. Local mesh refinement is crucial in fracture mechanics to resolve the fracture zone with sufficient accuracy. We apply overlay meshes providing a powerful means to introduce adaptive mesh refinement by superposition. We use the finite cell method to overcome the immanent trimming problem in NURBS surface models [2]. The combination of both, the finite cell method and the local refinement strategy allows us to include easily soft and hard inclusions as common e.g. in surface coatings of self-healing structures. We demonstrate the performance of our approach with several benchmark studies and examples from engineering practice.

REFERENCES


ISOGEOMETRIC ANALYSIS AND QUADRATURE RULES FOR THE SYMMETRIC GALERKIN BOUNDARY ELEMENT METHOD

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ABSTRACT

Boundary element methods (BEMs) are nowadays considered as a valid alternative to classical domain methods, such as finite differences (FDMs) and finite elements (FEMs), above all in physical and engineering applications involving, for instance, problems defined on unbounded domains with bounded boundary. If the fundamental solution of the differential operator at hand is known, a wide class of elliptic, parabolic, hyperbolic, interior and exterior problems can be reformulated by integral equations defined on the boundary of the given domain. The numerical method most frequently used to solve such types of equations has been for many years certainly the collocation method, together with different singular integration techniques. Indeed the Galerkin method has been generally avoided because it requires a double integration process, which appeared difficult to evaluate efficiently. There are however applications, for example in crack propagation problems, elasticity, elastodynamics, etc., where the use of a Galerkin method may give some important advantages. So in the last two decades Galerkin BEMs have been studied and, among them, Symmetric Galerkin BEM has revealed to be very effective, especially for mixed boundary value problems and for coupling with FEM, [1]. On the other side, the new Isogeometric analysis approach (IgA), which establishes a strict relation between the geometry of the problem domain and the approximate solution representation, has also brought a renewed interest for BEMs, since one has to consider only a discretization of the domain boundary, and this can be done in an accurate way by geometric modeling techniques. Great part of IgA literature has been focused on FEMs and only recently the IgA approach has been introduced in the framework of BEMs (see e.g. [2] and references therein), and in particular has been applied successfully in SGBEM ([3]). In order to take all the possible benefits from using B-splines instead of Lagrangian basis, an important point is the development of specific new quadrature formulas for efficiently implementing the assembly phase of the method. Note that this promising direction has already been taken into account in the IGA-FEMs context, but different formulas are needed here because the elements of the final linear system are defined by singular or even hypersingular integrals. In this talk we shall present the first results of this development. This is a joint work with Alessandra Aimi, Mauro Diligenti (University of Parma), Francesco Calabrò (University of Cassino) and Alessandra Sestini (University of Florence).

REFERENCES


PRECONDITIONERS FOR ISOGEOMETRIC ANALYSIS
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ABSTRACT

Iterative solvers have attracted the attention of the isogeometric community. Standard algebraic preconditioners (Jacobi, SSOR, incomplete factorization) commonly adopted for finite elements exhibit reduced performance when used in the context of the isogeometric k-method [2]. Many other papers show the difficulty in achieving both robustness and computational efficiency for the high-degree k-method. In this context, we say that a preconditioner $P$ for the linear system $Au = b$ is robust if the condition number $\kappa (P^{-1}A)$ is bounded from above by a reasonably low number not depend on the degree or continuity of the spline space adopted in the isogeometric discretization; we say that a preconditioner is computationally efficient if its setup and application has a computational cost comparable to the one of the matrix-vector multiplication for the system matrix $A$, i.e. $O(Np^3)$.

Two recent papers [3] and [6] have proposed innovative multigrid methods. The two works ground on the following common ingredients: first, in order to guarantee robustness, they use specific spectral properties of the discrete operator of the isogeometric k-method; second, they exploit the tensor-product structure of isogeometric spaces in order to achieve efficiency in 2D and 3D.

In this work we further focus on the tensor-product structure of multivariate spline and consider approaches that have been developed for the so-called Sylvester equation. This is indeed a well-studied problem in the numerical linear algebra literature, as it appears in many applications, e.g. stochastic PDEs, control theory, etc. [7]. In our context, consider the Laplace operator with constant coefficients, on the reference cube $[0, 1]^3$ parametrised by the identity mapping, then the tensor-product spline Galerkin discretization leads to a (tensorial) Sylvester equation:

$$(K_1 \otimes M_2 \otimes M_3 + M_1 \otimes K_2 \otimes M_3 + M_1 \otimes M_2 \otimes K_3) u = b \quad (1)$$

where $K_l$ and $M_l$ denote the univariate stiffness and mass matrices in the l direction, and $\otimes$ is the Kronecker product. Observe that in general, for variable coefficients, general elliptic problems, non-trivial and possibly multipatch geometry parametrization, the isogeometric system is not as in (1). In this case, a fast solver for (1) plays the role of a preconditioner. Having this motivation in mind, our aim is to study how the linear solvers for the Sylvester equation perform for (1) originated by an isogeometric k-method. We select two among the most effective algorithms: the first is the direct solver proposed by Bartels and Stweart in [1], the second is the alternating direction implicit (ADI) iterative solver, first proposed in [4]. The potential of ADI for isogeometric problem has already been recognized in [5]. We analyse and benchmark both the 2D and 3D cases. The direct method accuracy is, up to round-off error, independent of degree and continuity of the spline space adopted, while ADI is robust with a number of iterations that grows logarithmically with respect to $p$ and $N$. Surprisingly, the direct method exceed in performance ADI. This is shown in 2D, and even more so in 3D. In the latter case the Bartels-Stweart direct solver has a computational cost of $O(N^{4/3})$ FLOPs that is asymptotically higher than the ADI cost, which is $O(Np)$ FLOPs per ADI iteration. But, when used as a preconditioner
in benchmarks that are representative of realistic problems, the direct solver performs significantly better. By analysing in detail the computational cost of the two approaches, we give an explanation of this behaviour. Both approaches are suited to parallelisation which significantly speed up the execution time, though this is not considered in our analysis.

Our conclusion is that the use of a Bartels-Stewart direct solver as a preconditioner in a linear iterative solver for the isogeometric method is a very effective approach, deserving attention and worthing further investigation. In a forthcoming work we will address the robustness of this approach with respect to the geometry parametrization or the coefficient of the PDE.

REFERENCES


ESTIMATION OF ARTERIAL ELEMENT-BASED ZERO-STRESS STATE WITH T-SPLINES WALL DISCRETIZATION

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ABSTRACT

In patient-specific arterial fluid–structure interaction computations the image-based arterial geometry does not come from a zero-stress state (ZSS), requiring, as done in rudimentary ways in [1, 2], an estimation of the ZSS. A method for estimation of element-based ZSS was introduced in [3] and used in coronary arterial dynamics computation with medical-image-based time-dependent anatomical models in [4]. The method has three main components. 1. An iterative method, which starts with a calculated initial guess, is used for computing the ZSS such that when a given pressure load is applied, the image-based target shape is matched. 2. A method for straight-tube segments is used for computing the element-based ZSS so that we match the given diameter and longitudinal stretch in the target configuration and the “opening angle.” 3. An element-based mapping between the artery and straight-tube is extracted from the mapping between the artery and straight-tube segments. This provides the mapping from the arterial configuration to the straight-tube configuration, and from the estimated ZSS of the straight-tube configuration back to the arterial configuration, to be used as the initial guess for the iterative method that matches the image-based target shape. With NURBS wall discretization, we can obtain the element-based mapping directly, instead of extracting it from the mapping between the artery and straight-tube segments. That is because all we need for the element-based mapping, including the curvatures, can be obtained within an element. With T-Splines, we add to the method more geometric flexibility, such as being able to deal with artery branches. In the test case we present to demonstrate how the method works, we use a patient-specific aorta model.

REFERENCES


A NEW ROTATION-FREE ISOGEOOMETRIC THIN SHELL FORMULATION AND A CORRESPONDING CONTINUITY CONSTRAINT FOR PATCH BOUNDARIES

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ABSTRACT

Here we present a general non-linear computational formulation for rotation-free thin shells based on isogeometric finite elements [1]. It is a displacement-based formulation that admits general material models. The formulation allows for a wide range of constitutive laws, including both shell models that are extracted from existing 3D continua using numerical integration and those that are directly formulated in 2D manifold form, like the Koiter, Canham and Helfrich models (used for lipid bilayers).

Further, a unified approach to enforce the $G^1$-continuity between patches, the angle between surface folds, enforce symmetry conditions and prescribe rotational Dirichlet boundary conditions, is presented using penalty and Lagrange multiplier methods.

The formulation is fully described in the natural curvilinear coordinate system of the finite element description, which facilitates an efficient computational implementation. It contains existing isogeometric thin shell formulations as special cases. Several classical numerical benchmark examples are considered to demonstrate the robustness and accuracy of the proposed formulation. The presented constitutive models, in particular the simple mixed Koiter model that does not require any thickness integration, show excellent performance, even for large deformations.

REFERENCES

SHARP AND DIFFUSE INTERFACE METHODS: TWO FUNDAMENTAL PARADIGMS FOR NON-BOUNDARY-FITTED MODELING AND DISCRETIZATION

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ABSTRACT

The concept of non-boundary-fitted modeling and discretization appears in many current simulation technologies that require the treatment of complex geometric features. The techniques available can be classified into two groups. Sharp interface methods require the geometrically accurate resolution of interfaces and associated discontinuous solution fields, relating them (at least conceptually) to core concepts of isogeometric analysis. Diffuse interface methods approximate geometric features and discontinuous solution fields by a continuous phase-field function with steep gradient that evolves from the solution of an additional differential equation.

In the first part of this talk, we highlight some of the computational advantages and limitations of the two approaches, which differ significantly despite the common main objective (a clever treatment of complex domains). In the second part of this talk, we focus on the ability of diffuse interface methods to establish automated imaging-through-analysis simulation workflows. In this context, we discuss the seamless interaction of unsupervised image processing, variational representations of diffuse geometry (e.g., based on phase-field solutions of the Allen-Cahn equation) and adaptive finite element methods. We present several representative examples based on CT and MRI scans, such as generating a perfusion profile of the human liver, strength and fracture simulations in multiscale bone structures, and the analysis of phase segregation processes in Li-ion batteries.
CONSTRUCTION AND USE OF OPTIMAL MULTI SCALE ENRICHMENT FUNCTIONS

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ABSTRACT

The approximation power of a generalized finite element method (GFEM) or partition of unity method (PUM) essentially stems from the use of problem-dependent enrichment functions. In the context of problems with micro-structure such enrichment functions must be employed on the whole domain and capture the effects of the micro-structure. We present a general framework for the numerical construction of such enrichments based on various numerical homogenization approaches and compare the performance of the resulting multi-scale basis functions.

An important practical issue when using numerically computed enrichment functions is the fact that the enrichments are not known a priori but rather become available during the simulation. Therefore, it is very challenging to impose stability constraints on these enrichments so that the stability of the overall scheme must be attained for arbitrary enrichments \cite{1}. Similarly, for explicit dynamics or eigenvalue problems a reliable lumping scheme for the mass must be available for efficiency \cite{2}. We present respective constructions and show their impact in various application settings and the overall parallel scalability of the numerical scheme.

REFERENCES


ISOGEOMETRIC MODELING AND ANALYSIS OF A REAL-WORLD APPLICATION: AN AUTOMOTIVE HOOD INNER

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ABSTRACT

Of particular interest in the automotive industry is the effective integration between design (CAD) and analysis (CAE). Isogeometric Analysis (IGA) provides a means of accomplishing this integration since, in theory, the same mathematical description of the geometry is used in both design and analysis. Moreover, IGA has been popularized as more accurate and cost-effective than traditional finite element analysis (FEA). However, the industrial adoption and acceptance of IGA has been slow to date, primarily because of the lack of general-purpose commercial tools for isogeometric modeling and analysis. In particular, a key to the effective usage of IGA is the suitability of the native CAD data for analysis. Commercial usage of IGA requires an isogeometric toolset capable of interfacing with major CAD packages, generating analysis-suitable geometry (ASG) from CAD data, and providing superior analysis capabilities. Such a toolset must include capabilities commonly found in traditional finite element pre-processors such as the representation of complex industrial structural assemblies of parts and components joined together by fasteners, welds, and adhesives. In this talk we will discuss the results of a feasibility study which was conducted to determine whether real-world CAD models can be transitioned to state-of-the-art ASG descriptions and then analyzed directly and accurately using isogeometric analysis. For the purpose of this initial study a complex automotive hood-inner sheet metal part was selected as a testbed problem. We will discuss the techniques used to convert the hood, originally built as a trimmed NURBS surface, into an ASG format. We will then describe the results of several benchmark simulations used to assess the accuracy and robustness of structural isogeometric finite elements in comparison to standard structural finite elements found in major commercial finite element packages.

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ON THE CONSISTENCY BETWEEN NEAREST-NEIGHBOR PERIDYNAMIC DISCRETIZATIONS AND DISCRETIZED CLASSICAL ELASTICITY MODELS

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ABSTRACT

Peridynamics is a nonlocal reformulation of classical continuum mechanics. At the continuum level, it has been demonstrated that classical (local) continuum mechanics is a special case of peridynamics. Such a connection between these nonlocal and local theories has not been extensively explored at the discrete level. We investigate the consistency between nearest-neighbor discretizations of linear elastic peridynamic models and finite difference discretizations of the Navier-Cauchy equation of classical elasticity. We demonstrate that using the standard meshfree approach in peridynamics, nearest-neighbor discretizations do not reduce, in general, to discretizations of corresponding classical models. We study nodal-based quadratures for the discretization of peridynamic models, and we derive quadrature weights that result in the desired consistency. The quadrature weights that lead to such consistency are, however, model-/discretization-dependent. We motivate the choice of those quadrature weights through a quadratic approximation of displacement fields. The stability of nearest-neighbor peridynamic schemes is also demonstrated through a Fourier mode analysis. Finally, an approach based on a normalization of peridynamic constitutive constants at the discrete level is explored. This approach results in the desired consistency for one-dimensional models, but does not work in higher dimensions.
RANDOM ISOGEOMETRIC ANALYSIS (RIGA) FOR SEEPAGE IN UNSATURATED SOILS

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ABSTRACT

Isogeometric Analysis (IGA) has been increasingly employed for simulation purposes in various fields over the past decade. However, majority of previous studies utilize IGA in a deterministic manner by using average input values in analysis. In this study, we combine IGA and the random field theory to account for variability of input parameters and propose a new method called Random Isogeometric Analysis (RIGA). The proposed RIGA is then applied to simulate seepage in unsaturated soil. Two constitutive models, the Soil Water Characteristic Curve (SWCC) and Hydraulic Conductivity Function (HCF), are primarily used to describe the behavior of unsaturated soils under different matric suction ranges. The effects of variability of SWCC and HCF model parameters are studied. Random field concepts with statistical homogeneity (fixed mean, standard deviation, and spatial correlation) are used to generate SWCC and HCF model properties. Simulations represent a 2D transient problem subjected to a constant infiltration rate. Results of parametric studies depict the statistical outputs relating to seepage quantities and negative pore pressure with respect to standard deviation and correlation between SWCC and HCF model parameters. In all cases, results are compared with those obtained from deterministic analysis and it is shown that negative pore pressure, flow rate, and other quantities of interest show considerable changes by both standard deviation and correlation structure of model parameters.
MODELING DAMAGE EVOLUTION OF AN ULTRA-HIGH PERFORMANCE CONCRETE IN A MESHFREE FRAMEWORK

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ABSTRACT

Accurately predicting the response of concrete structures to impact and blast phenomena is of great interest to the engineering community. Modeling ultra-high performance concrete (UHPC) is of particular interest. Analysts must choose a robust numerical method to accurately model extreme deformations due to impact and blast. Meshfree methods naturally have the capability to model extreme material deformation and fragmentation without the need of ad hoc treatments. The reproducing kernel particle method (RKPM) has been shown to be an effective tool to model continuum-scale penetration events [1] as well as modeling meso-scale micro cracking [2] of cementitious material. For any numerical method, selecting the appropriate material model is one of the most critical aspects of modeling concrete in extreme events. In particular, the damage portion of a concrete material model is a critical parameter. Recently developed methods have shown great promise to model damage in concrete using a robust micro-crack informed damage model (MIDM) [2,3]. The MIDM is a multiscale approach that uses RKPM to model the meso-scale voids of concrete in a representative volume element. The meso-scale models are then used to produce damage evolution curves through an energy bridging technique. Using laboratory experiments and x-ray microcomputed tomography, a damage evolution model is developed and presented for an UHPC by using the MIDM. The resultant damage evolution model is then used to simulate laboratory experiments including quasistatic flexure tests and projectile penetration tests. The newly developed model is also compared to previously used damage models.

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REFERENCES


MESHFREE PERIDYNAMICS FOR SOFT MATERIALS

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ABSTRACT

The peridynamic theory of solid mechanics was proposed in the year 2000 [1] as a generalization of the standard theory. Its distinguishing feature is the ability to model discontinuities, discrete particles, and long-range forces within its basic field equations. These field equations are integro-differential, rather than differential, equations. They lend themselves to a meshfree discretization [2] that is used in the majority of applications of peridynamics to date. This discretization, in spite of some non-ideal aspects of its accuracy and convergence [3,4], is compatible with fracture and avoids excessive effects of grid orientation. It is also easy to code.

This talk will focus on recent progress in applying the meshfree discretized form of peridynamics to low-modulus materials that undergo large deformation in combination with damage, such as elastomers and gels. The use of material models that retain invertibility in an incremental sense – changes in deformation state inducing some nonzero change in the force state – minimizes some practical difficulties with the meshfree discretization. Formulating a material model to include contributions from both Eulerian and Lagrangian representations of the response allows weak materials subjected to large excursions in loading to be modeled. Contact forces, including friction, are easily included within these material models. It is demonstrated that a meshfree peridynamic model of a gel specimen can undergo extensive fracture and fragmentation, followed by large compression of the fragments, with reasonable results.

Application of the meshfree method to a variety of applications such as bird strike against aircraft and crack turning in rubber will be discussed. The generation of ejecta from the free surface of a metal subjected to a strong incident shock wave will be demonstrated. Examples showing the effect of surface tension on weak structures such as bubbles will be included.

REFERENCES


UNCERTAIN LOADING AND QUANTIFYING MAXIMUM ENERGY PENETRATION INSIDE COMPOSITE STRUCTURES

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ABSTRACT

A systematic method for identifying the worst case load amongst all boundary loads of a fixed energy is introduced. Here the worst case load delivers the largest fraction of input energy into a prescribed subdomain of interest. This leads to an eigenvalue problem, for which the largest eigenvalue is the maximum fraction of energy which can penetrate the subdomain. The associated eigenfunctions are the worst case solutions. The worst case load and associated energy penetration are computed through the numerical solution of the eigenvalue problem over several heterogeneous structures. The properties of these eigenfunctions serves as motivation for the multiscale spectral generalized finite element method introduced in \cite{babu} and \cite{babu2}.

REFERENCES


ALGORITHM FOR FAST SIMULATIONS OF SPACE-TIME ISOGEOMETRIC FINITE ELEMENT METHOD WITH T-SPLINES

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ABSTRACT

In our work we consider computational complexities of multi-frontal direct solvers for two-, three-, and four-dimensional grids with T-splines refined towards different singularities [1]. This work is the extension of the results already obtained for hierarchical basis functions [2, 3]. We propose a general element partition tree construction algorithm that generates orderings for the multi-frontal solver basing solely on the geometry of the computational mesh. We conclude that the computational complexity of our algorithm depends only on the kind of singularity and does not depend on the spatial dimension. In particular, we show that point and edge singularities result in $O(N)$ complexity, face singularities generate $O(N^{1.5})$ computational complexity and hyperface singularity in 4D results in $O(N^2)$ complexity, where $N$ is the number of T-splines. We conjecture that those are the best possible time complexities that can be attained for this type of solvers on those meshs. Furthermore, we analyze the computational complexities of time dependent problems: in particular, we compare the traditional methods using iterative time integration algorithm on a sequence of grids (e.g. Euler or Crank-Nicolson) with an alternative approach of solving the problem as a 3D or 4D space-time formulation. Our conclusion is that the alternative approach may reduce the computational cost by an order of magnitude for some refined grids.

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REFERENCES


ENRICHEO ISOGEOMETRIC SIMULATIONS OF DIFFUSION DRIVEN PHASE EVOLUTION

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ABSTRACT

The complex physics of diffusion driven phase evolution involves, in addition to bulk diffusion of species, possible interfacial reaction and surface diffusion of compounds. The dynamics of the phase formation, growth and motion is dependent on the chemical potential, state of stress as well as other fields near the interface. The primary challenges to modeling the phase evolution are the tracking of the interface and the application of boundary conditions on the moving interfaces. A phase-field solution to these problems relies on an implicit representation of the interface, and arguably causes an increase in the mathematical complexity of the governing equations as well as the numerical solution procedure. The phase-field equations are often non-linear and non-convex, and the phase-field variables require a large number of additional degrees of freedom to represent the geometry relative to a sharp interface model.

In this work, a novel computational technique is developed to efficiently solve diffusion driven phase evolution problems. The method relies on explicit modeling of the phase boundary and so normals and curvatures are explicitly computed at any point on the boundary, which enables a strong imposition of the interfacial conditions. To accurately capture the local high concentration gradient around the interface, the simulations are carried out using truncated hierarchical B-splines (THB-splines) along with a Smart-Cut refinement algorithm. The truncated hierarchical B-splines are stored in a Kd-tree structure, which is shown to have lower worst-case space complexity than Quad-tree or Oct-tree representation. Procedures for adaptive time stepping, refinement and coarsening of geometry are also developed to increase the stability and efficiency of the proposed methodology. The method is demonstrated through several numerical examples including intermetallic growth and electromigration problems.
MOLECULAR DYNAMICS MODELING OF A CLAY-WATER-AIR CAPILLARY MENISCUS UNDER NON-ISOTHERMAL CONDITIONS

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ABSTRACT

The water menisci among clay particles impact the mechanical and hydraulic properties of unsaturated clays. For instance, the water bridge between two clay particles is under tension and this tensile capillary force increases the tensile strength of the clay particles by pulling them together. While the Young-Laplace equation can be applied to compute the capillary forces acting on clay particles, it requires the knowledge of the clay-water-air meniscus, such as, contact angle and meniscus curvature, which is rather difficult to obtain. The mechanical and hydraulic properties of unsaturated clays under non-isothermal conditions have practical implications in geotechnical engineering (e.g., geothermal energy, landfill cover design, and nuclear waste disposal). Molecular dynamic (MD) technique is proven to be an effective method in investigating clay structures and their behaviors. In this study, we investigate the impact of temperature variation on the clay-water-air system via the molecular dynamics modeling with the CLAYFF force field. In particular, the meniscus formed between two parallel pyrophyllite clay particles and pure water are studied via MD under different temperatures. The temperature range is from 300 K (e.g., ambient temperature) to 372 K, and the water-vapor interface is not considered in this study. We will report the impact of the temperature on the capillary force, contact angle, and meniscus curvature between two parallel clay particles as well as surface tension between the water-air interface under different geometric set ups for the clay-water-air systems (e.g., the different gaps between clay particles and strength parameters for the clay-water van der Waals force). In particular, the capillary force between clay particles obtained from MD simulations will be compared with the results by the Young-Laplace equation which requires the knowledge of the contact angle and surface tension obtained directly from the same MD simulation. This MD simulation of clay-water-air system has a significant implication in physical based multiscale modeling of unsaturated fine grained soils (e.g., clays) by providing physical properties of unsaturated fine soils at the interfacial scale.

REFERENCES


MODELLING AND SIMULATION WITH TRIANGULAR NURPS

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ABSTRACT

Isogeometric Analysis (IgA) is a simulation paradigm aiming to reduce the gap between the worlds of Finite Element Analysis (FEA) and Computer-Aided Design (CAD). The main idea is to use the CAD representations not only to model physical domains but also to approximate the solution of differential problems. Tensor-product B-splines and Non-Uniform Rational B-Splines (NURBS) are common tools in CAD, and so they are in IgA. Unfortunately, the tensor-product structure precludes a strictly localized refinement. This motivates the interest in alternative spline structures for IgA.

In this talk we review the use of quadratic Powell–Sabin (PS) splines in the context of IgA [1, 4–6]. These splines are defined on triangulations endowed with a particular macro-structure and can be represented with basis functions possessing properties similar to the classical (tensor-product) B-splines. A rational extension, the so-called Non-Uniform Rational PS (NURPS) splines, can also be easily defined. They allow an exact representation of quadrics, and their shape can be locally controlled by control points and weights in a geometrically intuitive way [3]. Higher order B-splines on triangulations with PS macro-structure can be found in [2].

Thanks to their structure based on triangulations, NURPS splines offer the flexibility of classical finite elements with respect to local mesh refinement and are not confined to quadrilateral parametric domains. Moreover, they share with tensor-product NURBS the increased smoothness and the B-spline-like basis. Hence, they constitute a natural bridge between classical FEA and NURBS-based IgA. We will illustrate the use of PS/NURPS splines in IgA with several numerical examples.

REFERENCES


MULTISCALE GFEM FOR HIGH CONTRAST SUSPENSIONS USING OPTIMAL LOCAL BASIS FUNCTIONS

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ABSTRACT

We evaluate a multiscale GFEM using optimal spectral bases functions developed in [1] and [2] within a partition of unity setting. This method is applied to compute local fields inside high contrast particle suspensions. We develop both direct and implicit solvers and evaluate their performance for various contrasts between reinforcement particles and matrix material. We demonstrate the numerical implementation for several examples. For suspensions of particles with a minimum distance between neighboring particles the numerical experiments agree with new theoretical estimates that show the convergence rate is exponentially decreasing and independent of the elastic properties of particle and matrix materials.

REFERENCES


ALGEBRAIC POINT PROJECTION FOR EXPLICITLY TRACKED INTERFACES AND IMMERSED BOUNDARIES

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ABSTRACT

In solution approaches where a moving interface is explicitly tracked on an underlying domain, or alternatively in immersed boundary problems, the influence of a spatial point on the explicitly defined interface or boundary immersed in the domain requires projection of the point onto the parametrically defined surface. In this work, a non-iterative, algebraic technique for point projection is presented for low degree NURBS curves and surfaces. The given NURBS entity is first subdivided into Bezier segments. Next, the Bezier segments are implicitized using the resultant theory. The intermediate matrix during the implicitization process is utilized to project the spatial point to that on the curve or surface. Finally, the located point is inverted to parametric space by solving the resultant equation. The proposed method has exact on-curve/surface solution and accurate near-curve/surface solution. Examples are presented to illustrate the efficiency and robustness of the developed method. The computational expense is demonstrated on the examples to be comparable or lower than that required for a single Newton-Raphson iteration. The method is shown to be robust and able to generate valid solutions even for curves and surfaces with high local curvature or $G^0$ continuity – problems where the Newton-Raphson method fails due to discontinuity in the projected points or because the numerical iterations fail to converge to a solution, respectively. Several numerical examples, including diffusion and phase transition problems, are presented to demonstrate the developed technique.
FEASIBLE CONSTRAINTS FOR SMOOTH CONVEX APPROXIMATIONS VIA SEMIDEFINITE PROGRAMMING

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ABSTRACT

For scalar- or vector-valued functions in \(\mathbb{R}^d\), smooth convex approximations are formed by a linear combination of nonnegative basis functions. The nonnegativity endows such approximations with the convex hull and variation-diminishing properties, which is present in Bernstein polynomials, B-splines, Sibson interpolant, and maximum-entropy approximants to name a few. Higher-order B-splines are well-known in the univariate setting, which extend to higher dimensions through a tensor-product construction. Even in \(\mathbb{R}^2\), for scattered set of nodes, the means to devise feasible constraints to reproduce monomials that will yield smooth nonnegative basis functions remains an open problem. Rosolen et al. [1] provide the necessary conditions on the constraints that can reproduce arbitrary quadratic polynomials.

On using the convex hull interpretation of the constraints in Reference [1], we setup the formulation to obtain a feasible set by appealing to powerful positivity certificates from real algebraic geometry due to Schmüger [2] and Putinar [3]. Such positivity certificates provide some weighted SOS (sum-of-squares) representation for polynomials positive on a compact semi-algebraic sets and it turns out that they can be implemented via semidefinite programming, an efficient technique for solving a certain type of convex conic programs. We use these tools from polynomial optimization, and then apply the maximum-entropy formalism to compute the basis functions. The resulting procedure yields a family of convex univariate quadratic and cubic approximations; in particular, constraints that produce Bernstein polynomials, B-splines and the Ball basis will be presented. Extensions to devising feasible constraints to compute nonnegative basis functions on polygons in two dimensions will also be discussed.

REFERENCES


A MESHFREE APPROACH FOR HIGHER-ORDER GRADIENT CRYSTAL PLASTICITY

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ABSTRACT

A scale dependency of plastic deformation, i.e., a smaller crystal grain provides a higher flow stress, is an important characteristic of metallic materials. From both the theoretical and experimental viewpoints, it is known that dislocation structures at crystalline scale play an important role in the scale effect. Crystal plasticity models are powerful tools to investigate meso-scale mechanical behaviors of metallic materials, however, a conventional crystal plasticity involves no scale effect. Incorporating a higher-order gradient effect is an efficient way to introduce a scale effect into a crystal plasticity framework, and several studies on the higher-order gradient crystal plasticity have been conducted in the recent decade.

In the higher-order gradient plasticity, an additional governing equation expressing the dislocation field is introduced. Kuroda and Tvergaard proposed a higher-order crystal plasticity model, in which the dislocation density field was introduced as an additional unknown variable [1]. This model can represent the scale effect of metallic materials very well. Finite element method is generally used to solve this type of constitutive model; however, it was reported that a kind of combination of finite elements for displacement and dislocation density fields led to failure of numerical analysis and a special treatment may be required for solving both fields simultaneously.

In this study, the reproducing kernel particle method (RKPM) is introduced to solve the higher-order crystal plasticity. Using the RKPM, an arbitrary combination of bases for displacement and dislocation density fields can be introduced without difficulty. Several kinds of combination of bases are adopted for solving the higher-order gradient crystal plasticity. The RKPM with any basis combination considered in the present study always shows better performance than FEM. The convergence rates of RKPM and FEM are also investigated, and an advantage of RKPM for the present material model is discussed.

REFERENCES


A COMPARATIVE STUDY ON MULTI-MATERIAL TOPOLOGY OPTIMIZATION WITH PERIMETER PENALIZATION: ISOGEOOMETRIC SIMP VS FEM BASED PHASE FIELD METHOD

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ABSTRACT

A new multi-resolution NURBS-based density approach for topology optimization of multi-material structures is presented. In this method, the density fields of material phases are parameterized in the NURBS space and projected to the underlying analysis space. An extension of the perimeter penalization technique is introduced where restrictions are imposed on the perimeters of density fields of all phases. Consequently, not only can one control the complexity of the optimal design but also the minimal lengths scales of all material phases. It will be seen that this idea leads to optimal designs with significantly enhanced manufacturability and comparable performance. Moreover, it will lead to removing numerical artifacts such as checkerboards and will provide full analytical computation of sensitivities in a cost effective manner.

As will be observed, this idea dramatically simplifies the imposition of such restrictions. As a result, unlike the common element-wise or nodal based density representations, owing to higher order continuity of density fields in this method, their required gradients for the evaluation of perimeters are calculated exactly without additional computational cost, irrespective of the employed numerical method in the underlying analysis space.

Due to the employed decoupled representations of the design and analysis space, different numerical methods such as classic FEM or isogeometric method (IGA) could be used in the analysis space. The problem is formulated for compliance minimization of two-dimensional structures consisting of multiple homogeneous distinct materials and addressed using both Solid Isotropic Material with Penalization (SIMP) as well as phase field method based on the volume constrained Allen–Cahn system. A comparative study between the obtained results of the two methods using the same regularization technique is performed.

REFERENCES


PREDICTION FOR DEFORMATION MODES OF AUTOMOTIVE FRAMES USING THE ISOGEOMETRIC ANALYSIS AND FAST NURBS GENERATOR

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ABSTRACT

In order to reduce automobile body weight and improve the crashworthiness of lightweight vehicles, crash simulation has become an indispensable tool in automotive industries. The use of high strength steels in lightweight vehicles leads to dramatic fuel savings and is greatly increasing in the vehicles these years. Meanwhile the high strength steels become less ductile in general. As the results, the fracture of steel material and spot weld failure may occur due to local deformation. Therefore, the accuracy improvement of local deformation to predict the fracture locus is highly demanded by automotive industries. However, current shell elements of FEM use bilinear shape functions which are difficult to predict a complicated local deformation with high accuracy. To resolve this problem, IsoGeometric analysis considered. A system to simplify a CAD data maintaining the same tolerance has been developed. Using the simplified CAD data, an IsoGeometric model meeting the requirements of a simulation was created.

First, to investigate the applicability of IsoGeometric analysis in crashworthiness, simplified models were utilized. They contain S-frame model for collapse problem, 3-point bending model for fracture, L-T model for spot weld failure and hat-section model for axial crash problem. These simulation results based on the IsoGeometric analysis correlated well with the experimental tests. Next, a fast Nurbs Generator (IGA optimization tool) to comprehensively transfer the data between CAD and IsoGeometric analysis was developed by the authors.

As the design CAD models (B-rep) of automobile body are complex, they are not practical for the direct use in CAE analysis. In this study, we have developed a tool to prepare the data for IsoGeometric analysis from the design CAD information. In other words, the developed tool is employed to simplify the CAD data while maintain the original tolerance to optimize the control points for IsoGeometric analysis. The steps listed below shows the internal process flow, and this process significantly reduces the lead time to create IsoGeometric models for impact analysis utilizing the design CAD models.

1. Fix geometrical errors in CAD data, and then simplify the geometry
2. Replace all faces by four-sided faces
3. Align control points at the edge to match between adjacent faces
4. Export data for IsoGeometric analysis

In this presentation we will address the following three points: evaluation of the IsoGeometric analysis results against the experimental results, functionalities of Fast Nurbs Generator and its algorism, and the future challenges of IsoGeometric analysis.
LARGE-SCALE PHASE-FIELD COMPUTATIONS OF DENDRITE GROWTH BY GPU SUPERCOMPUTER

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ABSTRACT

Phase-field method has emerged as a powerful tool for simulating the time evolutions of complicated material microstructure. In the phase-field model, an order parameter, called phase-field, is introduced to distinguish the different phases, and the interface migration is expressed by solving a time evolution equation of the phase-field variable. Thanks to the recent development of quantitative phase-field methods [1], we can obtain the quantitative results independent of interface thickness. Nevertheless, to accurately express the material microstructures, we need much finer numerical meshes comparing to a representative size of microstructure, such as a curvature radius of dendrite tip. Therefore, we need a large-scale computational technique for the phase-field simulation. Recently, graphics processing units (GPU) have been used for general-purpose computations. We have developed a parallel GPU scheme to accelerate a very-large-scale phase-field simulation of the directional solidification of a binary alloy and showed that parallel GPU computation is well suited for phase-field simulations [2]. In this presentation, we introduce our recent progresses regarding the large-scale phase-field simulations of dendrite growth [4-5].

REFERENCES


AORTA AND HEART VALVE FLOW ANALYSIS WITH THE SPACE–TIME TOPOLOGY CHANGE (ST-TC) METHOD AND NURBS IN SPACE

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ABSTRACT

Aorta and heart valve flow analysis is computationally challenging because the contact between the valve leaflets creates topology change (TC) in the mesh and the aorta inner surface we start with has roughness inherent in medical imaging. The Space–Time TC method [1] addresses the TC challenge and still maintains the high-resolution representation of the boundary layers near solid surfaces. The ST-TC method introduced in [1], which was successfully used in flow analysis of heart valve models [2], was in the context of finite element discretization. Here we introduce the ST-TC version where, as basis functions in the ST context, we use NURBS in space (ST-NS) [3]. The ST-NS basis functions give us more accuracy in flow computations and smoother representations of the leaflets and aorta inner surface. For the aorta-inner surface, the ST-NS basis functions not only provide a higher-order representation of the surface, but also, in the process of obtaining that representation, remove the roughness. In addition, more-structured nature of the ST-NS representation simplifies the “master–slave” system in the ST-TC method, and, because the flow representation in the TC zone has a wider support, results in a more robust flow computation method. We use the ST-TC method and the ST-NS basis functions with the ST Variational Multiscale (ST-VMS) method [4, 5], which serves as the core method. The analysis we present is for a patient-specific aorta model and a valve/leaflet model that we created.

REFERENCES


A SPARSE-GRID VERSION OF IGA METHODS

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ABSTRACT

Sparse grids have been proposed in the early 90's in the context of finite differences (FD) / finite elements (FE) methods to reduce the “curse of dimensionality effect”, i.e., the fact that the number of degrees of freedom (DoF) of the approximation grows exponentially in the number of dimensions of the problem.

Roughly speaking, the sparse-grid construction consists in recasting the construction of conventional FE/FD methods in a hierarchical fashion and suitably discarding the components which carry the least amount of information. Under suitable regularity assumptions (slightly more demanding than the usual Sobolev spaces) sparse grids are then able to deliver approximations with essentially the same accuracy of conventional FE/FD methods (i.e., up to a logarithmic factor appearing in the error estimates), using however a much lower number of DoF. Furthermore, the sparse-grid solution can be computed as a linear combination of standard FE/FD solutions on relatively coarse grids (the so-called “combination technique”): this implies that sparse grids can be implemented quite straightforwardly reusing existing solvers and leads to a very natural parallelization of the computation.

In this talk we detail the application of the sparse-grid technology to the h-refined version of the classical IGA method and show some numerical tests that will highlight how sparse IGA performs compared to the classical “full tensor” counterpart.
THE SIMULATION OF STRAIN LOCALIZATION FOR GRANULAR MATERIAL WITH MICRO- MACRO TWO-SCALE METHOD OF DISCRETE ELEMENT-COSSEURAT CONTINUUM FINITE ELEMENT

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ABSTRACT

In view of individual particle essentially provided with rotational freedom and considering the kinematic connections and the transformation consistency of the physical parameters between micro-macro models as well as the requirement of introducing some type of regularization mechanism into the classical macroscopic continuum model to preserve the well-posedness of the localization problem, we develop a multiscale method which adopts the discrete element incorporating both rolling resistances (rolling friction tangential force and rolling resistance moment) and sliding friction tangential force between particles in the contact model from the microscopic point of view, whereas the micro-polar continuum from the macroscopic point of view to describe the granular materials. This can preserve the well-posedness of the localization problem and benefit the transformation consistency of the physical parameters between micro-macro models. Also, a consistent return mapping algorithm for the integration of the rate constitutive equation and the closed form of the consistent elastoplastic tangent modulus matrix for Cosserat continuum model is presented. The effectiveness of the developed two-scale method is demonstrated by several examples.

Key words: Strain localization; Micro-macro two-scale method; DEM; Cosserat continuum; Granular material
FAST FORMATION OF ISOGEOMETRIC GALERKIN MATRICES BY WEIGHTED QUADRATURE

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ABSTRACT

In this talk we present a new algorithm for the formation of matrices stemming from isogeometric Galerkin methods. This algorithm does not employ the element-wise assembling loop which is standard in finite elements codes, and that is inherited by most isogeometric codes. Instead, we loop over the matrix rows and we use a specifically designed weighted quadrature rule for each row. The test function is incorporated in the integration weight while the trial function, the geometry parametrization and the PDEs coefficients form the integrand function. This approach is very effective in reducing the computational cost, while keeping the optimal order of approximation of the method. This significant computational saving is confirmed by numerical tests on 3D problems.
EFFICIENT DATA STRUCTURES FOR ANALYSIS-SUITABLE GEOMETRY

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ABSTRACT

Representation of analysis-suitable geometry models for IGA presents two fundamental problems: efficient data structures for unstructured meshes and concise storage of the computational basis on the mesh. This presentation will demonstrate the use of combinatorial maps[1] to encode unstructured meshes. Combinatorial maps generalize half edges[2] for arbitrary dimension. For IGA, combinatorial maps provide a topological foundation for construction of the subsequent parameterization, geometry, and computational basis.

Basis representations on unstructured meshes constitutes the largest space cost of analysis suitable geometry. We introduce extraction expressions, a novel representation of the computational basis and extraction operators[3] as a directed acyclic graph (DAG) of Bernstein expressions. Extraction expression DAGs store each sub-expression exactly once, eliminating the storage overhead of sub-expressions that often repeat throughout the basis. In addition to memory space savings, each unique sub-expression is only evaluated once as the basis is extracted across the entire analysis suitable geometry. Using the foundations of combinatorial maps and extraction expressions we demonstrate the ability to apply isogeometric analysis methods to industrial problems.

REFERENCES


SPACE–TIME COMPUTATIONAL ANALYSIS WITH NURBS IN SPACE AND TIME

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ABSTRACT

Space–Time (ST) Variational Multiscale (ST-VMS) method [1] and its predecessor ST-SUPS [2] have a good track record in computational analysis of complex fluid–structure interactions (FSI) and flows with moving boundaries and interfaces (MBI). When an FSI or MBI problem requires high-resolution representation of boundary layers near solid surfaces, ALE and ST methods, where the mesh moves to follow the fluid–solid interface, meet that requirement. Moving-mesh methods have been practical in more classes of complex FSI and MBI problems than commonly thought of. With a number of complementary methods introduced recently, the ST methods can now do even more than that. They can deal with contact between solid surfaces or other topology changes, as enabled by the ST-TC method [3], or a spinning solid surface that is in contact with a solid surface, as enabled by the ST Slip Interface TC (ST-SI-TC) method [4]. Using NURBS as basis functions is further increasing the accuracy and scope of the ST methods [5]. In the ST context, the options for using NURBS as basis functions are in space (ST-NS), in time (ST-NT), and in space and time (ST-NST). A general-purpose NURBS mesh generation method introduced recently makes the use of ST-NS and ST-NST options more practical in computations involving complex geometries. That practicality is further increased by the ST-SI method [6]. We present an overview of all these methods and some test computations.

REFERENCES


DEVELOPMENT OF A COMMERCIAL PLATFORM FOR
ISOGEOMETRIC ANALYSIS

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ABSTRACT

Despite significant promise and interest [1,5], isogeometric analysis has not yet achieved significant penetration in the larger industrial scene. We believe that this is largely due to the lack of a commercial platform that realizes the vision of integrated design and analysis. We will discuss efforts to develop such a platform at Isogeometrx LLC including scaling academic innovations to industrial scale [1,2,3,4], novel solutions for representation and interfaces for analysis-suitable geometry, and problems addressed with industrial partners. Advances in representation and parameterization of complex parts and models including assemblies will be presented.

REFERENCES


IMPROVED XFEM: ACCURATE AND ROBUST DYNAMIC CRACK GROWTH SIMULATION

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ABSTRACT

The extended finite element method (XFEM) is widely accepted in academy as the major technique for crack analysis. Starting from 2009, commercial codes started to use this technique for crack analysis, singling the mature and acceptance of the technique in industries. However, the direct extension of the singular tip enrichment of XFEM, the core of the method, to dynamic crack growth simulation has long been a difficulty due to: (a) elevated bad conditioning as crack propagating, (b) extra-dof dynamics and energy inconsistency, and (c) “null” critical time step size and optimal mass lumping at crack tip. Based on an extra-dof-free partition of unity enrichment technique (R. Tian, Comput. Methods Appl. Mech. Engrg. 266 (2013) 1–22), we have improved XFEM through a crack tip enrichment without extra dof (R. Tian, L. Wen, Comput. Methods Appl. Mech. Engrg. 285 (2015) 639-658). This paper is to answer the question whether the improved XFEM can also be easily extended to dynamic problems. Numerical tests show that the new XFEM is not only straightforward in implementation in dynamic problems, also provides the most accurate dynamic SIF in the benchmark problems and is orders of magnitude faster with an iterative solver.

Keywords: XFEM, extra-dof free enrichment, dynamic crack growth, partition of unity

REFERENCES
HIGH ORDER B-SPLINE MPM

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ABSTRACT

The material point method (MPM) is a hybrid Lagrangian-Eulerian method, in which Lagrangian particles so-called material points are used to carry the physical properties of a continuum. An Eulerian background grid is used to solve the equations of motion. MPM has been shown to be successful in simulating problems which involve large deformations and history-dependent constitutive models.

To approximate the integrals during the computations, material points are used as integration points. The quality of this numerical integration rule decreases when the material points become arbitrarily distributed.

Furthermore, it is common practice in the MPM to adopt piecewise linear basis functions to project the quantities at the grid nodes onto the material points. A major problem arises from the discontinuity of gradients at element boundaries, leading to unphysical oscillations in the internal forces when material points cross the boundary of an element. Grid crossing errors significantly affect the quality of the numerical solution. In fact, grid crossings can even lead to a complete lack of convergence.

In this talk we present a novel approach to design a high order MPM method making use of quadratic B-spline basis functions. The continuity of their gradients eliminates grid crossings errors, and hence, enables a more accurate reproduction of physical quantities such as stress and velocity. By using spline interpolation, integrals can be more accurately approximated, leading to a more accurate numerical solution. To achieve optimal convergence, we suggest the use of a consistent mass matrix instead of the lumped one, whereby the explicit solution of the linear system is avoided by using Richardson iteration. The improvements in terms of higher accuracy and rate of convergence are demonstrated for 1D benchmarks describing small and large deformations. In particular, we consider a vibrating bar problem and the deformation of a column of soil.
MULTI-SIDED HOLES AND SINGULAR PARAMETERIZATIONS

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ABSTRACT

One of the upshots of CAD representations of arbitrary genus geometries with a finite number of tensor-product polynomial patches is the introduction of multi-sided holes. The boundaries of these holes may be smooth or non-smooth. The former typically implies that the hole is surrounded by a periodic, tensor product configuration, while the latter usually corresponds to the presence of extraordinary vertices. A myriad of approaches have been explored concerning design and analysis of such geometries [2,3,4,5] and this topic is of considerable interest in the field of isogeometric analysis [1].

The hole-filling problem can, in principle, be easily solved by the use of singular parameterizations. However, in order to retain a certain order of smoothness, the admissible control point configurations need to satisfy additional restrictions. In particular, improper imposition of the smoothness constraints may lead to over constrained spline spaces, translating to rigid designs and sub-optimal analysis.

We present recipes for treatment of the hole-filling problem that employ singular parameterizations. For holes with smooth boundaries, we construct $C^k$ polar spline patches of non-uniform degree. On the other hand, for polygonal holes, we present a simple $C^1$ construction inspired by [5]. The constructed spline spaces demonstrate optimal approximation behavior, and seem to be well behaved even at the singularities. Examples corresponding to applications in design and analysis will be presented.

REFERENCES


PRECONDITIONING IMMERSED METHODS FOR FLUID-STRUCTURE INTERACTION

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ABSTRACT

Immersed methods such as the finite cell method [1] have shown to be a valuable extension to isogeometric analysis (IGA). Besides enabling IGA on trimmed domains in computer aided design by the weak enforcement of boundary conditions on unfitted boundaries, there are additional advantages in computational fluid-structure interaction models. First of all immersed methods can preclude laborious remeshing procedures. Furthermore these methods simplify the application of fully compatible and therefore divergence free [3] function spaces.

Immersed methods, however, can lead to ill-conditioned matrices, which impedes solving procedures. This is particularly the case when used in combination with higher-order polynomial discretizations, which are almost intrinsic to IGA. The development of preconditioning techniques appears to be essential in enabling these methods for large scale simulations [1].

We present a detailed analysis of the conditioning problems in the finite cell method, which reveals the underlying mechanism that causes ill-conditioning. This analysis quantifies the dependence of the condition number for symmetric and coercive weak forms on the trimmed volume of an element that only intersects the physical domain on a small fraction of its untrimmed volume. This dependence indicates that without proper preconditioning, ill-conditioning is inevitable for immersed methods.

Based on the mechanisms causing ill-conditioning, we have developed efficient algebraic preconditioners for immersed methods. Different approaches are required, depending on symmetry and positive definiteness of the system matrix. Furthermore, we present a technique to apply these preconditioners to mixed methods. Because these preconditioner are fully algebraic, they are not interwoven with the rest of the method, which makes them robust and straightforward to implement. It is numerically shown that the preconditioned condition number does not depend on the relative position of the physical domain on the grid and scales with the grid size in the same way as in regular finite element methods [2].

REFERENCES


ALGORITHMS FOR ADAPTIVE ISOGEMETRIC METHODS USING HIERARCHICAL SPLINES AND IMPLEMENTATION IN GEOPDES

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ABSTRACT

One of the most active research topics on isogeometric analysis (IGA) is the development of adaptive methods for local refinement and coarsening. These methods require the use of spline spaces that go beyond the traditional tensor product structure. Several alternatives have been already proposed in the IGA community, such as T-splines, hierarchical splines, LR-splines or PHT-splines. Among them, hierarchical splines are probably the easiest to define and to implement, due to their multilevel structure.

In this work we introduce a set of structures and algorithms for the implementation of adaptive IGA methods based on hierarchical splines. Two main structures are defined: one for the hierarchical mesh, and one for the hierarchical basis. They rely on analogous structures for the tensor product spaces of each level, plus some methods related to the support of the basis functions. Methods to relate elements and functions of two consecutive levels are also required. With the help of these methods, we introduce algorithms to update the sets of active elements and basis functions during refinement and coarsening, which can be done either marking elements of the mesh or marking basis functions. The advantage of our algorithms with respect to [1] is that only local information is used during the update of the active sets. Moreover, the structures we define are simpler than those in [2], because mesh refinement is applied to the elements of the mesh, and no information about vertices is required.

All the algorithms have been implemented in the open source Octave (and Matlab) software GeoPDEs [3], and will be added to the package in a future release.

REFERENCES


A FINITE POINTSET MODEL FOR REACTIVE MIXING

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ABSTRACT

The Finite Pointset Method (FPM) [1] -developed and implemented at Fraunhofer ITWM- is a meshfree finite difference method for the numerical solution to problems in continuum mechanics such as fluid flows. In FPM, the finite set of computation nodes (point cloud) moves along the trajectory of the fluid flow (lagrange coordinates) and the meshfree character of the method allows to easily adapt the point cloud to changes in the domain of computation such as the movement of free surfaces or rapid geometry movement, e.g. a rotating stirrer. Over the last decade, the software package has been applied successfully to several problems in industry such as processes of water crossing, sloshing and filling.

The software package and the method are under continuous development and in pursuit of new types of application for FPM, this contribution will present fundamentals of the method and the current state of an FPM model for simulating processes of reactive mixing. Such processes are fundamental operations in chemical engineering and simulations are required in that context to design the mixing devices, in particular to improve the process of the scale-up from laboratory scale to industrial scale.

REFERENCES


ISOGEOMETRIC ENHANCED QUASI-CONVEX MESHFREE ANALYSIS

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ABSTRACT

Convex meshfree approximation is very desirable due to its variation diminishing property and excellent solution accuracy. However, the commonly used moving least square or reproducing kernel meshfree approximants are not convex. The max-entropy meshfree approximation yields convex shape functions by employing exponential basis functions. Nonetheless, the construction of max-entropy meshfree shape functions requires an iterative computation, and moreover its higher order generalizations are not straightforward. Here we present an isogeometric enhanced quasi-convex meshfree method with nearly positive shape functions. The current quasi-convexity of the meshfree approximation is achieved by introducing the mixed monomial basis vector of isogeometric B-spline basis functions into the consistency conditions within the reproducing kernel meshfree framework. The mixed monomial basis vector consists of the reproducing points of B-spline basis functions which are strictly convex. The resulting meshfree shape functions have a similar form as the standard reproducing kernel meshfree shape functions, while the negative portions of the meshfree shape functions are dramatically reduced. The proposed formulation is applicable to arbitrary order basis functions without iterative operations for the shape function construction. Meanwhile, no artificial parameters and nodal gap functions are required in the present formulation. The numerical implementation of the proposed quasi-convex meshfree methodology is almost identical to the standard reproducing kernel particle method, but with better accuracy. The efficacy of the proposed method is demonstrated through several examples.

Acknowledgements: The support of this work by the National Natural Science Foundation of China (11472233, 11222221) and the Natural Science Foundation of Fujian Province of China (2014J06001) is gratefully acknowledged.
FROM DIFFUSE DAMAGE TO SHARP COHESIVE CRACKS: A COUPLED XFEM FRAMEWORK FOR FAILURE ANALYSIS OF QUASI-BRITTLE MATERIALS

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ABSTRACT

Failure of quasi-brittle materials is governed by crack formation and propagation which can be characterized by two phases: (i) diffuse material degradation process with initial crack formation and (ii) severe localization of damage leading to the propagation of large cracks and fracture. While continuum damage mechanics provides an excellent framework to describe the first failure phase, it is unable to represent discontinuous displacement fields. In sharp contrast, cohesive zone models are poorly suited for describing diffuse damage but can accurately resolve discrete cracks. The present work is devoted to a coupled continuous/discontinuous approach for modeling the two failure phases of quasi-brittle materials in a coherent way. The proposed approach involves an integral-type nonlocal continuum damage model coupled with an extrinsic discrete interface model. The transition from diffuse damage to macroscopic cohesive cracks is made through an equivalent thermodynamic framework established in multidimensional settings, in which the dissipated energy is computed numerically and weakly matched. The method is implemented within the extended finite element framework, which allows for crack propagation without remeshing. A few benchmark problems involving straight and curved cracks are investigated to demonstrate the applicability and robustness of the coupled XFEM cohesive-damage approach. Force-displacement response, as well as predicted propagation paths, are presented and shown to be in close agreement with available experimental data. Furthermore, the method is found to be insensitive to various damage threshold values for damage-crack transition, yielding energetically consistent results.

REFERENCES

RKPM FORMULATION FOR FULLY COUPLED HYDRO-MECHANICAL ANALYSIS OF FLUID-SATURATED POROUS MEDIA

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ABSTRACT

Numerical modeling of reservoirs with low permeability or under undrained conditions often suffers from spurious fluid pressure oscillations due to the improper construction of approximation spaces. To address this issue, a fully coupled, stabilized meshfree formulation is developed based on a fluid pressure projection method, in which an additional stabilization term is added to the variational equation to correct the deficiency of the equal-order u-p reproducing kernel approximation [1]. The projection scheme is formulated under the framework of the stabilized conforming nodal integration [2] which enables a significant enhancement of the computational efficiency and accuracy, and the spurious low-energy modes of nodal integration are also eliminated under a framework which unifies addition stabilization of SCNI [3] and the pressure projection. The effectiveness of the proposed stabilized meshfree formulation is demonstrated by solving several benchmark problems.

REFERENCES


TRUNCATED HIERARCHICAL VOLUMETRIC SPLINES OVER
UNSTRUCTURED HEXAHEDRAL MESHES

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ABSTRACT

In this paper, we propose truncated hierarchical volumetric splines (THVS) over unstructured hexahedral meshes, with support of simple and highly localized refinement. The unstructured (manifold) hexahedral meshes can be arbitrarily complex. A watertight geometry is always guaranteed for the input mesh, and the geometry remains the same for all levels of refinement. In the THVS local refinement, high-level blending functions are added while low-level ones may be discarded or truncated, depending on the refined subdomain. At each refinement step, at least one-ring neighborhood of a certain vertex needs to be refined such that a high-level blending function can be added into the THVS space. THVS blending functions are piecewise polynomials that form a partition of unity. Due to the truncation mechanism, support overlapping among blending functions at different levels is reduced, and thus it results in sparser stiffness matrix. Bézier extraction can be incorporated into THVS such that THVS can be applied in the existing finite element framework. THVS is demonstrated to be suitable for adaptive isogeometric analysis by all the tested examples.

REFERENCES

MULTIMATERIAL ASPECTS OF MESHFREE MODELING OF UNDERBODY BLAST

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ABSTRACT

This presentation discusses the meshfree modeling and results of underbody blast experiments with a rigid target that the U.S. Army Engineer Research and Development Center (ERDC) conducted for software validation. The problem setup consists of a rigid device at a given standoff from the ground with the explosive buried below the soil surface. The modeling involves significant mixing interactions of soils, explosive detonation products, air, and metal components. The soil was characterized and modeled using the Hybrid-Elastic-Plastic geomaterial model, which uses a Prandtl-Reuss failure surface and a Tillotson equation of state. The explosive is modeled with a Jones-Wilkins-Lee equation of state and the air is modeled as an ideal gas. The target material is represented using the Johnson-Cook material model and a Mie-Gruneisen equation of state. The explosive and air are modeled using a generalized particle algorithm within EPIC for the full simulation. The soil begins as finite elements and converts to particles once it reaches a prescribed plastic strain. The general methodology employed at ERDC to obtain accurate impulse results is also discussed as well as the significance of the soil’s effect on the imparted impulse to an overhead structure from a buried explosive device. Consistent, repeatable, well-characterized, instrumented experiments were executed to improve our understanding and to make this software validation possible.
PARALLEL ISOGEOMETRIC SIMULATIONS AND INVERSION OF HAZARDOUS ENVIRONMENTAL EFFECTS DURING OIL/GAS EXTRACTION

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ABSTRACT

In this work we investigate the multi-criteria optimization problem when we maximize the amount of the oil extracted through the hydraulic fracking and at the same time we minimize the environmental side effects. We optimize the locations of pumps and sinks in the model so we can drain the maximum amount of the liquid and at the same time we minimize the contamination of the groundwaters. In particular, as the primal problem solver we utilize the parallel isogeometric L2 projection explicit method [1] for modeling three dimensional non-linear flow in heterogenous media [2]. The explicit solver has been parallelized for multi-core linux cluster nodes using GALOIS framework [3]. For the inverse problem solution we employ the Evolutionary Multi-Agent System (EMAS) for distributed genetic algorithm simulations. The genetic code in EMAS models the location of three pumps and one sink, and the evaluation of an agent consists in execution of the parallel isogeometric L2 projection solver with the prescribed locations of the pumps and sinks, integrating the total contamination of the groundwaters through and the amount of the drain liquid. The EMAS finds the Pareto front that maximizes the amount of the drain fluid and minimizes the contamination. For the assumed map of the formation with the groundwaters below the formation, our software has found that the optimal location of the sink is in the center of the formation, and it proposed multiple equivalent combinations of three pumps above the sink, far from the groundwaters, and far from the sink itself. The total simulation took 25 evolutionary steps with parallel evaluations of 20 agents, each evaluation executing the parallel explicit solver on 16 cores, using 10,000 time steps. Each execution of the parallel L2 projections took around 40 seconds using 16 cores. The total time was 25*40 seconds = 16 minutes on 20 linux cluster nodes with 16 cores.

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A MESHFREE CONTINUOUS-DISCONTINUOUS APPROACH FOR THE DUCTILE FRACTURE MODELING IN EXPLICIT DYNAMICS ANALYSIS

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ABSTRACT

This paper presents a combined continuous-discontinuous modeling technique for the dynamic ductile fracture analysis using an interactive particle enrichment algorithm and a strain-morphed nonlocal meshfree method \cite{1}. The strain-morphed nonlocal meshfree method is a node- integrated meshfree Galerkin method \cite{2,3} which was recently proposed for the analysis of elastic-damage induced strain localization problems. In this paper, the strain-morphed nonlocal meshfree formulation is extended to the elastic-plastic-damage materials for the ductile fracture analysis. When the ductile material is fully degraded, the interactive particle enrichment scheme is introduced in the strain-morphed nonlocal meshfree formulation that permits a continuous-to- discontinuous failure modeling. The essence of the interactive particle enrichment algorithm is a particle insertion-deletion scheme that produces a visibility criterion for the description of a traction-free crack and leads to a better presentation of the ductile fracture process. Several numerical benchmarks are examined using the explicit dynamics analysis to demonstrate the effectiveness and accuracy of the proposed method.

REFERENCES


ROCK SLOPE STABILITY ANALYSIS BASED ON ICMP AND GRAPH THEORY

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ABSTRACT

A jointed rock slope stability analysis method was developed based on the independent cover meshless particle method (ICMP) and graph theory. In the ICMP method, the analysis model is described with arbitrary discrete nodes, and a general polynomial is employed as the meshless interpolation function for each discrete node which results in a very simple formulation and numerical implementation. The complex rock joint, rock interface and supporting structure can be easily modeled and simulated in the ICMP. In this work, the ICMP is used to calculate the stress distributions of rock slope with joints, the slope stability analysis is converted to a graph problem, the Bellman-Ford algorithm is used to obtain the slip surface, and the safety factor is defined as the ratio of the resistant force and the slip force along the slip surface. The proposed method is easy to build complex 2D/3D geotechnical engineering numerical model, and removes the difficulties of the iterative calculations for the stability analysis of rock slope. Several typical numerical examples are presented to demonstrate the capability and robustness of the method in rock slope stability analysis.
IMMERSOGEOMETRIC FLUID–STRUCTURE INTERACTION DESIGN OPTIMIZATION OF A HYDRAULIC ARRESTING GEAR

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ABSTRACT

In this presentation, we focus on a study of a full-scale hydraulic arresting gear used to retard the forward motion of an aircraft landing on an aircraft-carrier deck. The simulations make use of the recently purposed immersogeometric fluid–structure interaction (FSI) techniques [1], which were originally proposed to simulate heart valve FSI problems [1–3]. A recently developed interactive geometry modeling and parametric design platform for isogeometric analysis (IGA) [4] is employed to create the arresting gear model, and illustrates a natural application of IGA to this problem class. The fluid mechanics and FSI simulation results are reported in terms of the arresting-gear rotor loads and blade structural deformation and vibration. Excellent agreement is achieved with the experimental results for the arresting gear design simulated in this work. Using our recently introduced isogeometric design optimization framework, a new design of the arresting gear rotor blade is proposed to reduce the maximum stress and stress variance on the structure due to FSI.

REFERENCES


ANALYSIS OF LARGE DEFORMATION FAILURE PROCESSES USING SMOOTHED PARTICLE GALERKIN FORMULATION

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ABSTRACT

The mathematical models of large deformation failure processes are often ill-posed and the corresponding numerical solutions are generally non-smooth. In essence, severe mesh distortion would occur if Lagrangian finite element method (FEM) is used. Furthermore, ad-hoc erosion criteria are usually needed to model the failure processes for the mesh-based formulation. In this work, the smoothed particle Galerkin (SPG) meshfree method [1] in LS-DYNA is applied in the analysis of this type of problems. SPG formulation is a pure particle formulation based on the nodal integration of nonlocal Galerkin weak form. Numerically, the SPG formulation [1-4] is designed to alleviate the zero-energy modes in the nodally integrated meshfree formulations and to naturally handle the material separation during the failure processes. Two types of failure procedures are analyzed with the SPG formulation implemented in LS-DYNA in this work, namely, impact penetration and FDS (flow drill screw) drilling. Impact penetration is a very complex multi-physics procedure, which involves localized damage, large degree of material fragmentation (failure) and separation (ejecta), complicated projectile – target interaction. FDS drilling is frequently used in joining high strength sheet metals, which involves failure of the base material and thermal responses due to friction. These procedures are very difficult for FEM due to aforementioned issues. Very reasonable responses are obtained and some of them are found to be in good agreement with available experimental data, which indicates the potential of the SPG formulation in modeling material failure processes.

REFERENCES

ISOGEOMETRIC MORTAR METHODS IN VIBROACOUSTICS

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ABSTRACT

Although often ignored, complicated domains can not always be reasonably represented by a single NURBS patch. For this reason, handling multi-patch geometries is a key ingredient to practical applications of isogeometric analysis. Isogeometric mortar methods, see, e.g., [1], are weak coupling methods which allow a flexible and accurate NURBS-patch coupling without any requirement on the interface meshes.

One particular application considered in this work is the vibroacoustic analysis of a violin bridge, i.e., a small wooden component of a violin which has an important influence on the acoustics. The complicated and curved geometry motivates the use of several NURBS patches glued by isogeometric mortar methods. In vibroacoustics, one is interested in the eigenvalues and eigenfunctions of a solid body, often with unknown or varying material parameters. Already early works, see, e.g., [4], pointed out advantages of isogeometric methods in eigenvalue analysis. In this work, the additional influence of the weak coupling on the approximation of the spectrum using isogeometric mortar methods is investigated on simple domains and compared to the case of single-patch splines and finite element functions. The wooden material of the violin bridge is modeled as an orthotropic material which features nine material parameters. An extra parameter is included as the thickness of the geometry which is transformed into the constitutive equation. It results in a ten parameter eigenvalue problem which is solved in a multi-query context. An efficient solution, in this context, is guaranteed by the use of reduced basis techniques for eigenvalue problems, see [2, 3].

REFERENCES


FLUID–STRUCTURE INTERACTION SIMULATIONS OF A PATIENT-SPECIFIC AORTIC ROOT WITH VALVE DESIGNS

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ABSTRACT

In this work we present fluid–structure interaction (FSI) modeling and simulation of a patient-specific aortic root with valve designs. The patient-specific aortic root geometry is reconstructed from the medical image data using a non-uniform rational B-spline (NURBS) surface. We then parametrically design prosthetic valves according to the aortic root, using a Rhino/Grasshopper-based interactive geometric design platform. Due to the complex motion of the heart valve leaflets, the blood flow domain undergoes large deformations, including changes of topology. Our immersogetic method directly analyzes a spline-based surface representation of the heart valve geometry immersed into an unfitted trivariate NURBS discretization of the surrounding fluid domain. A hybrid immersogetic/arbitrary Lagrangian–Eulerian methodology allows us to efficiently perform a computation that combines a boundary-fitted, deforming-mesh treatment of the artery with a non-boundary-fitted treatment of the leaflets. We simulate the coupling of the deforming, patient-specific aortic root and valve, and the surrounding blood flow under physiological conditions through an entire cardiac cycle. The attachment edge of the valve is coupled with the arterial wall motion using a penalty approach. The results demonstrate the effectiveness of the proposed techniques in practical computations with greater levels of physical realism. We emphasize the importance of arterial tissue prestress in patient-specific vascular and valvular FSI simulations. Finally, the simulation results of flow patterns in the artery are compared with phase-contrast MRI data.
r-Refinement Method for Isogeometric Analysis with Harmonic Mapping and Monitor Functions

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ABSTRACT

In isogeometric analysis, NURBS representation of the computational domain allows to perform refinement operations to improve the analysis result without changing the geometry. There are three kinds of methods to improve the simulation results by increasing degree of freedom: h-refinement by knot insertion, p-refinement by order elevation, and k-refinement combining order elevation and knot insertion [1]. The common feature of above three methods is that the degree of freedom (control points in IGA) is increased while keeping the geometry of computational domain. For a specified IGA problem, r-refinement method by moving interior control points to the optimal position is firstly proposed in [2] to improve the parameterization of computational domain while keeping the degree of freedom. However, it is only applicable to small-scale problems; on the other hand, invalid parameterization may be achieved by only minimizing a posteriori error estimation. In this paper, motivated by the moving mesh method in finite element analysis, we propose a new r-adaptive method for isogeometric analysis. The main contribution can be summarized as follows:

1. A framework of r-refinement method with harmonic mapping and monitor function is proposed for isogeometric applications. Different from the direct optimization method [2], the proposed r-refinement method by PDE solving is more efficient and the resulting parameterization is analysis-suitable due to the properties of harmonic mapping.

2. Two kinds of new monitor functions are proposed according to the feature of isogeometric analysis: the first one is based on the absolute curvature metric of isogeometric solution surface, the second one is based on a posteriori error estimation for isogeometric analysis problems.

The proposed method is tested on two-dimensional heat conduction problems and several examples are shown to illustrate the effectiveness of the proposed method.

REFERENCES


ISOGEOMETRIC FREE-SURFACE FLUID-STRUCTURE INTERACTIONS

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ABSTRACT

We propose an isogeometric free-surface fluid-structure interaction framework, which enables the simulations of the interaction between free-surface flow and floating structures with great efficiency, accuracy and robustness. The free-surface flow is modeled by two-phase Navier-Stokes equations with assistance of level set method. ALE-VMS is employed to discretize the Navier-Stokes equations and level set convection equation. The structural motion is described by isogeometric rotation-free shell, beam and cable formulation. Non-matching discretization is employed at fluid-structure interface. The kinematic compatibility between fluid and structure is weakly enforced at fluid-structure interface. Quasi-direct coupling strategy with matrix-free technique is adopted to handle the large added mass. The mathematical formulation is discussed in detail. Several engineering applications are shown.
A Quasi-Linear Reproducing Kernel Particle Method, and its Application to Fragmentation and Material Flow Modeling

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ABSTRACT

The reproducing kernel particle method (RKPM) relies on polynomial reproducing conditions to yield desired accuracy and convergence properties. For order of completeness higher than zero, appropriate kernel support coverage of neighboring particles is necessary to prevent kernel instability caused by singularity of the moment matrix. This requirement can be challenging to meet in numerical simulations involving large deformations or material fragmentation. In this work, a quasi-linear RKPM formulation is introduced to achieve nearly linear completeness while maintaining exact constant basis reproduction, and guaranteeing kernel stability for any kernel support coverage. The accuracy and robustness of the method is then demonstrated through numerical examples involving very large deformation, material fragmentation, and material flow, and results are compared to constant basis approximation simulations.
ERROR ANALYSIS FOR AN IMMERSOGEOMETRIC CARDIOVASCULAR FLUID–STRUCTURE INTERACTION FRAMEWORK

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ABSTRACT

In this work, a divergence-conforming B-spline fluid discretization is employed, to address the long-standing issue of poor mass conservation in immersed methods for computational fluid–structure interaction (FSI) that represent the influence of the structure as a forcing term in the fluid subproblem. An augmented Lagrangian formulation is used for FSI that enforces kinematic constraints with a combination of Lagrange multipliers and penalty forces. The bio-prosthetic heart valve is modeled as immersed thin shell structures, which leads to a penalty method. On the other hand, in this application there is a large pressure jump across the leaflets, reveals shortcomings of the penalty approach. To counteract steep pressure gradients through the structure without the conditioning problems that accompany strong penalty forces, the Lagrange multiplier field is resurrected. To study the convergence of the proposed immer-sogeometric method, precise analysis is carried out for the method when it is used to apply Dirichlet boundary conditions along immersed boundaries in linear parabolic model problems. The convergence rates for numerical errors in $H^1$ norm as well as in $L^2$ norm are proved, and we have also validated the error estimates with numerical examples for both linear and nonlinear problems.
RECENT DEVELOPMENTS IN VOLUMETRIC T-SPLINE PARAMETERIZATION

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ABSTRACT

In this talk, I will show our recent developments in volumetric T-spline parameterization, which contributes directly to the integration of design and analysis, the root idea of isogeometric analysis. For arbitrary topology objects, we first build a polycube whose topology is equivalent to the input geometry and it serves as the parametric domain for the following trivariate T-spline construction. Boolean operations, geometry skeleton and centroidal Voronoi tessellation (CVT) based surface segmentation can be used to build polycubes with surface features preserved. A parametric mapping is then used to build a one-to-one correspondence between the input geometry and the polycube boundary. After that, we choose the deformed octree subdivision of the polycube as the initial T-mesh, and make it valid through pillowing, quality improvement, and applying templates or truncation mechanism to handle extraordinary nodes. Weighted and truncated T-spline basis functions are derived to satisfy the requirements of analysis-suitable T-splines, including partition of unity and linear independence. The parametric mapping method has been further extended to conformal solid T-spline construction with the input surface parameterization preserved, and also incorporated with Rhino and Abaqus.

REFERENCES


COUPLING OF SHELL ELEMENT WITH MPM FOR BIRD STRIKE SIMULATION

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ABSTRACT

Bird strike becomes a serious threat to the safety of the aircraft, and takes an important place in the aircraft certification process. Bird strike is a strongly nonlinear process, in which the bird undergoes extreme deformation while the aircraft structures may be destroyed.

The Finite Element Method (FEM), Arbitrary Lagrange Eulerian (ALE) and Smooth Particle Hydrodynamics (SPH) methods are three most established numerical approaches to study this problem. However, the FEM encounters fatal problems of mesh distortion and entanglement, while the ALE is rather complex in capturing boundary and convection calculating, and the SPH is somewhat time consuming due to neighbor searching. There is no generally accepted uniform approach to bird strike simulation [1]. The Material Point Method (MPM) [2,3] avoids the abovementioned shortcomings of both the FEM and ALE methods, and shows advantages of computational efficiency and stability over the SPH method. It has been widely applied to the problems involving extreme material deformation [3]. Thus, the MPM is employed to model the bird in this talk.

An aircraft is mainly composed of thin-walled structures, so that the shell finite element is efficient and accurate to model these structures in small deformation. Hence, a shell element is incorporated in our MPM3D code, and coupled with MPM particles based on a particle-to-surface contact algorithm [4]. To fully take advantages of both the FEM and MPM, the adaptive finite element material point method [5] is extended to bird strike simulation, in which the distorted and failed shell elements are converted to MPM particles adaptively. The proposed approach is first validated by several numerical tests, and then used to simulate a bird strike on an aircraft wing leading edge structure.

REFERENCES

A RIEMANN-SNNI GALERKIN MESHFREE METHOD FOR SOLID AND FLUID DYNAMICS

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ABSTRACT

Shock waves occur in both solids and fluids under certain loading conditions such as high velocity impact and blast. While Galerkin meshfree methods have shown great advantages over the finite element methods in fragment-impact problems [1], the application of meshfree methods to shock dynamics has been formulated based on a Rankine-Hugoniot enriched Riemann solution using a stabilized conforming nodal integration (Riemann-SCNI) with a Godunov type scheme for oscillation control [2, 3]. This work presents an extension of Riemann-SCNI under the stabilized non-conforming nodal integration (Reimann-SNNI) framework for shock modeling in solids and fluids. In this approach, a decomposition of Cauchy stress into volumetric and deviatoric stress is performed, and the Godunov flux [4] is introduced to compute the volumetric internal force and energy. The performance of this method is examined by solving a set of benchmark problems in both solid and fluid dynamics.

REFERENCES

A PARTITION OF UNITY METHOD FOR THE PROPAGATION OF HYDRAULIC FRACTURES IN THERMOELASTIC MEDIA

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ABSTRACT

Hydraulic fracturing is subject to many different coupled physical phenomena. These include the thermo-elastic deformation of the surrounding rock, filtration, temperature conduction, fluid flow within the fracture and leak-off of the fracking fluid into the permeable rock [1]. Additionally, thermal properties of the fluid as well as of the surrounding rock can influence the behavior of the whole system and, especially, the crack propagation.

The simulation of the propagation of hydraulic fractures under those conditions puts many challenges on the numerical methods used [2]. We present a solution technique via the PUMA framework [3] based on a flat-top partition of unity method (PUM) [4] to discretize and solve the mixed, non-linear system of governing equations that are implied by this problem. The meshless approach presented allows us to apply the full power of the method, which includes enrichments stability guarantees and a linear multilevel solver, to each of the physical problem components.

We perform a sensitivity analysis of different types of boundary conditions, material parameters and injection strategies to the hydraulic fracturing process.

REFERENCES


ISOGEOMETRIC FINITE ELEMENT MODELING OF PHASE-FIELDS ON DEFORMING SURFACES

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ABSTRACT

A phase-field model on curved surface structures is presented. The geometric representation of the surfaces is described by curvilinear coordinates. The high order Partial Differential Equations (PDEs) of certain phase-field models require an at least C\textsubscript{1}-continuous spatial discretization. Using isogeometric finite elements such as NURBS an efficient computation of the underlying PDEs is achieved. Complex geometries necessitate the computational domain to be represented by several NURBS patches. The C\textsubscript{1}-continuity at patch boundaries is lost. A continuity constraint is presented to enforce the C\textsubscript{1}-continuity across patch interfaces. The phase separation of a binary mixture that is governed by the Cahn-Hilliard equation is studied on curvilinear surface structures with multiple NURBS patches. Numerical examples are presented for a torus, a sphere and a flat square. Geometrically exact shell formulations can be used to model a wide range of mechanical applications [1]. A coupled formulation of the mechanical field and the phase field is proposed for deforming thin solid-like shells.

REFERENCES

FREE-SURFACE FLOW SIMULATION WITH SPACE-TIME METHODS AND ISOGEOOMETRIC ANALYSIS

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ABSTRACT

The simulation of certain flow problems requires a means for modeling a free fluid surface; examples being viscoelastic die swell or fluid sloshing in tanks. In a finite-element context, this type of problem can, among many other options, be dealt with using an interface-tracking approach with the Deforming-Spatial-Domain/Stabilized-Space-Time (DSD/SST) formulation [1]. A difficult issue that is connected with this type of approach is the determination of a suitable coupling mechanism between the fluid velocity at the boundary and the displacement of the boundary mesh nodes. In order to avoid large mesh distortions, it makes sense to keep the nodal movements as small as possible; but of course still compliant with the no-penetration boundary condition. One common choice of displacement that fulfills both requirements is the displacement with the normal component of the fluid velocity. When using finite-element basis functions of Lagrange type for the spatial discretization, the boundary normal vector is only piecewise continuous, with jumps at the mesh nodes. This can create problems for the coupling, e.g., making it difficult to ensure mass conservation.

In contrast, NURBS basis functions of quadratic or higher order are not subject to this limitation. These types of basis functions have already been used in the context of free-surface boundaries, in connection with the NURBS-enhanced finite-element method (NEFEM) [2]. However, this method presents some difficulties due to the fact that it does not adhere to the isoparametric concept. As an alternative, we investigate the suitability of using the method of isogeometric analysis for the spatial discretization. If NURBS basis functions of sufficient order are used for both the geometry and the solution, both a continuous normal vector as well as the velocity are available on the entire boundary. This circumstance allows the weak imposition of the no-penetration boundary condition. We compare this option with some alternatives and also examine several coupling methods between the fluid equations, boundary conditions, and equations for the adjustment of interior control point positions.

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