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Comput. Methods Appl. Mech. Engrg. 275 (2014) 55–75

Computer methods in applied mechanics and engineering

www.elsevier.com/locate/cma

NURBS-enriched contact finite elements

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Received 14 March 2013; received in revised form 20 February 2014; accepted 27 February 2014
Available online 18 March 2014

Abstract

A novel enrichment of finite elements for contact computations based on isogeometric analysis is presented. Each body is divided into two parts, an enriched contact surface and the bulk domain together with surfaces that are not in contact. The latter part comprises the large majority of the domain and is treated in the usual manner with standard linear basis function, preserving the efficiency of classical finite element techniques. The enriched contact surface is discretized using NURBS basis functions of at least second order, allowing for a locally differentiable surface representation. This avoids the problem of suddenly changing normal vectors between element boundaries on the contact surface. Following the concept of isogeometric analysis, the smooth basis functions are not only used to describe the surface geometry, but also to approximate the solution on the surface. This leads to higher accuracy in the contact integral evaluation.

Numerical results are presented for 2D and 3D contact computations including frictionless sliding, adhesive peeling, and cohesive debonding. The presented contact element enrichment exhibits a major gain in numerical accuracy and stability without loss of efficiency compared to standard linear finite elements. The enrichment technique offers some advantages over Hermite and higher-order Lagrangian contact element enrichment techniques, such as locally differentiable surface representations in 3D, while featuring competitive accuracy and performance.

Keywords: Computational contact mechanics; Isogeometric analysis; Nonlinear finite element methods; Cohesive zone modeling; Sliding; Peeling

1. Introduction

This work presents a novel local finite element enrichment technique for contact computations that is both accurate and efficient. Computational contact of deformable solids plays an important role in engineering problems. Due to the complex nature of contact problems, numerical methods are often the only feasible

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http://dx.doi.org/10.1016/j.cma.2014.02.019
0045-7825/

approach to solve them. Efficient and highly accurate methods are therefore needed in research and industry alike.

The presented formulation combines the high accuracy achieved with isogeometric analysis with the efficiency of classical linear finite elements. The contact surface is locally enriched with NURBS-based isogeometric surface elements, while the bulk is discretized with linear elements. By using the enrichment for both, geometry and analysis, this leads to an accurate and continuous contact surface description and a higher accuracy in the contact integral evaluation. An at least C^1-continuous surface implies a continuous normal vector on the surface, making the projection of points to this surface simpler and more robust. The NURBS enrichment offers a viable alternative to using highly refined meshes, as it provides highly accurate results on comparably coarse meshes. It is shown that the use of NURBS enriched elements can even decrease the runtime of contact computations compared to standard linear elements due to faster convergence of the solver.

Isogeometric analysis (IGA) was first introduced by Hughes et al. [8] and is summarized in [3]. NURBS, the CAD modeling standard, are used as basis functions for finite elements. Recent advances include the introduction of the Bézier extraction operator [2], allowing IGA to be embedded conveniently into existing finite element codes by supplying a familiar element based representation. The extension to T-splines by Bazilevs et al. [1] offers the possibility of local mesh refinement.

A summary of non-linear computational contact mechanics is given in [10,23]. The use of IGA in contact computations has been investigated recently by De Lorenzis et al. [4], Lu [11], De Lorenzis et al. [5], and Temizer et al. [22]), and includes 2D and 3D, frictional and frictionless problems solved with various methods to describe and enforce the contact conditions, like mortar methods and the augmented Lagrangian method. In these papers the entire geometry is discretized with NURBS, as opposed to only discretizing the contact surface as proposed in this work.

An approach used to obtain continuous normal vectors on a C^0 facet-based contact surface is geometrical contact smoothing. Various techniques exist to obtain a locally at least C^1-continuous surface. These techniques use Hermite [12], Bézier [9], Spline [6], or NURBS [21] interpolation to approximate the contact surface. More recently, subdivision surfaces have also been used as a smoothing technique in [20]. While these formulations provide a continuous normal vector across element boundaries, the surface integrals are still approximated linearly. Also, consistent linearization of the contact terms becomes increasingly complex due to the influence of neighboring elements in the smoothing terms. The presented formulation provides a smooth surface representation without applying further smoothing techniques. The use of the NURBS basis functions to evaluate the surface integrals provides a higher-order approximation of these terms. Consistent linearization of the surface integrals then only depends on the two elements in contact.

Finite elements with one curved surface go back to [26,17,7]. They rely on a mapping of linear elements to a curved boundary. More recently the NURBS-Enhanced Finite Element Method (NEFEM) was proposed by Sevilla et al. [18]. It maps Lagrangian elements to a surface defined by NURBS and uses an adapted integration rule to take into account the curved boundary. Besides the low-order integration on the curved boundary, the NURBS surface is also considered rigid. Deforming the NURBS surface during computation, essential for computational contact, requires fitting the NURBS surface in each step. In the presented formulation, the displacement degrees of freedom are solved directly on the NURBS control points. The deformation of the surface is thus obtained automatically.

Previously proposed surface enrichments contain higher-order Lagrangian and Hermite interpolation [14,15], which both yield good results in contact computations. Though Hermite interpolation on the surface also results in a C^1-continuous surface representation, it lacks an extension to 3D. Lagrangian enrichment is possible in 2D and 3D, but C^0-continuity across element boundaries remains. The NURBS-enrichment yields C^1-continuity and higher in 2D and 3D.

The following section gives a brief overview of the computational contact models used in this paper and a summary of isogeometric analysis. Section 3 presents the NURBS-enriched contact elements and related refinement strategies. Numerical examples are discussed in Section 4. The results for NURBS-enriched contact elements are compared to those of standard linear finite elements and Lagrangian and Hermite enriched contact elements. Section 5 concludes the paper.