Computer Aided Geometric Design 43 (2016) 143–158

Contents lists available at ScienceDirect

Computer Aided Geometric Design

www.elsevier.com/locate/cagd

Direct immersogeometric fluid flow analysis using B-rep CAD models

Ming-Chen Hsu*, Chenglong Wang, Fei Xu, Austin J. Herrema,
Adarsh Krishnamurthy

Department of Mechanical Engineering, Iowa State University, 2025 Black Engineering, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Available online 15 February 2016

Keywords:
Isogeometric analysis
Immersed method
B-rep CAD model
Nitsche's method
GPU
Point membership classification

ABSTRACT

We present a new method for immersogeometric fluid flow analysis that directly uses the CAD boundary representation (B-rep) of a complex object and immerses it into a locally refined, non-boundary-fitted discretization of the fluid domain. The motivating applications include analyzing the flow over complex geometries, such as moving vehicles, where the detailed geometric features usually require time-consuming, labor-intensive geometry cleanup or mesh manipulation for generating the surrounding boundary-fitted fluid mesh. The proposed method avoids the challenges associated with such procedures. A new method to perform point membership classification of the background mesh quadrature points is also proposed. To faithfully capture the geometry in intersected elements, we implement an adaptive quadrature rule based on the recursive splitting of elements. Dirichlet boundary conditions in intersected elements are enforced weakly in the sense of Nitsche's method. To assess the accuracy of the proposed method, we perform computations of the benchmark problem of flow over a sphere represented using B-rep. Quantities of interest such as drag coefficient are in good agreement with reference values reported in the literature. The results show that the density and distribution of the surface quadrature points are crucial for the weak enforcement of Dirichlet boundary conditions and for obtaining accurate flow solutions. Also, with sufficient levels of surface quadrature element refinement, the quadrature error near the trim curves becomes insignificant. Finally, we demonstrate the effectiveness of our immersogeometric method for high-fidelity industrial scale simulations by performing an aerodynamic analysis of an agricultural tractor directly represented using B-rep.

1. Introduction

Immersogeometric analysis was first introduced by Kamensky et al. (2015) as a geometrically flexible technique for solving computational fluid–structure interaction (FSI) problems involving large, complex structural deformation. The method analyzed a surface representation of the structure by immersing it into a non-boundary-fitted discretization of the background fluid domain and focused on accurately capturing the immersed geometry (and hence the name *immersogeometric*) within non-boundary-fitted analysis meshes. The method was successfully applied to the FSI simulation of bioprosthetic heart valves (Kamensky et al., 2015; Hsu et al., 2014, 2015a). The immersogeometric method was further investigated

---

* Corresponding author.
E-mail address: jmchsu@iastate.edu (M.-C. Hsu).

http://dx.doi.org/10.1016/j.cagd.2016.02.007

by Xu et al. (2016) in the context of a tetrahedral finite cell approach (Varduhn et al., 2016) for the simulation of incompressible flow, both laminar and turbulent, around geometrically complex objects. The motivation was to alleviate the difficulties associated with computational fluid dynamics (CFD) mesh generation around complex design geometries. Typical mechanical computer-aided designs (CAD) are so complex that they cannot be handled by CFD mesh generation software independently and automatically, but require human analysts to perform intermediate steps such as defeaturing, geometry cleanup, and mesh manipulation (Marcum and Gaither, 2000; Wang and Srinivasan, 2002; Beall et al., 2004; Lee et al., 2010). The immersogeometric method was proposed to eliminate these labor-intensive procedures from the CFD simulation pipeline while still maintaining high accuracy of the simulation results.

In recent years, the development of isogeometric analysis (IGA) (Hughes et al., 2005; Cottrell et al., 2009) has paved a path towards a tighter integration of engineering design and computational analysis. The core idea of IGA is to use the same basis functions for the representation of geometry in CAD and the approximation of solution fields in finite element analysis (FEA). Aside from its potential to eliminate unnecessary labor from the design-through-analysis pipeline (Schillinger et al., 2012a; Breitenberger et al., 2015; Hsu et al., 2015b), IGA has attracted a great deal of attention due to the improvements in solution quality that follow from incorporation of smooth basis functions into engineering analysis (Cottrell et al., 2007; Akkerman et al., 2008). Over the last decade, IGA has been successfully employed in many areas of engineering and sciences, such as fluid mechanics and turbulence (Bazilevs et al., 2007a; Bazilevs and Akkerman, 2010; Akkerman et al., 2011; Evans and Hughes, 2013; Liu et al., 2013), structural and contact mechanics (Cottrell et al., 2006; Kiendl et al., 2009; Benson et al., 2010b; De Lorenzis et al., 2011; Temizer et al., 2012), fluid–structure interactions (Bazilevs et al., 2008, 2012), phase-field modeling (Gomez et al., 2008; Borden et al., 2014), collocation (Auricchio et al., 2010; Schillinger et al., 2013; Reali and Gómez, 2015), efficient quadrature rules (Hughes et al., 2010; Auricchio et al., 2012; Schillinger et al., 2014), boundary element methods (Simpson et al., 2012; Scott et al., 2013), shape and topology optimization (Dedè et al., 2012; Kiendl et al., 2014; Kostas et al., 2015), finite cell methods (Rank et al., 2012; Schillinger et al., 2012b; Schillinger and Ruess, 2015), trimmed geometries and patch coupling (Schmidt et al., 2012; Ruess et al., 2014; Guo and Ruess, 2015), analysis-suitable trivariate models (Zhang et al., 2007; Stein et al., 2012; Liu et al., 2014), T-splines (Bazilevs et al., 2010a; Scott et al., 2012; Li and Scott, 2014), and standardized file formats for data exchange between CAD and FEA packages (Benson et al., 2010a; Borden et al., 2011; Scott et al., 2011).

Despite the progress achieved in the last few years, several challenges remain in effectively using IGA to improve the engineering design process. Perhaps the biggest challenge is the construction of analysis-suitable geometric models. The typical industry standard for the representation of geometry in mechanical CAD systems is non-uniform rational B-splines (NURBS)-based boundary representations (B-reps). Although B-reps are ubiquitous in the CAD industry, they are not commonly used in analysis due to the challenges associated with directly using the B-rep information to perform geometric operations such as surface integration. Hence, the common practice in mechanical analysis (CFD or FEA) is to preprocess the B-reps by tessellating them into triangles and then using the triangular surface mesh in the simulations. Generating the surface tessellations of complex CAD models is time-consuming and labor intensive, since the geometry needs to be manually checked to avoid creating any intersecting or non-manifold features (such as hanging nodes) during tessellation. In addition, the tessellation of curved surfaces represented using spline surfaces introduces a tessellation error depending on the size of the triangles used to approximate them.

A pioneering work using NURBS-based B-rep models directly in nonlinear isogeometric shell analysis was presented by Breitenberger et al. (2015). However, directly using B-rep models in flow analysis is still limited because for flow simulations, the meshing of the surrounding fluid domain needs to be considered in addition to having the object surface discretization. Generating a high-quality boundary-fitted fluid mesh requires intense manipulation of the surface mesh. Although there have been advances in using analysis-suitable trivariate T-splines (Zhang et al., 2013; Wang et al., 2013; Liu et al., 2014) for volumetric discretization, using T-splines for CAD and CFD meshing continues to be limited by the geometric problems associated with the surface. To overcome these challenges, we present a novel method for immersogeometric fluid flow analysis that directly uses the CAD B-rep of a complex object and immerses it into a non-boundary-fitted discretization of the surrounding fluid domain. This work is inspired by Rank et al. (2012), who proposed to extend the finite cell method (Parvizian et al., 2007; Düster et al., 2008) to use CSG-tree and B-rep information for point membership classification, such that geometric models can be directly used in the finite cell analysis.

The immersogeometric method for CFD is comprised of the following main components. A variational multiscale (VMS) formulation of incompressible flow (Hughes et al., 2000, 2001, 2004; Bazilevs et al., 2007a) is used, which provides accuracy and robustness in both laminar and turbulent flow conditions. The Dirichlet boundary conditions on the surface of the immersed objects are enforced weakly in the sense of Nitsche's method (Nitsche, 1970; Bazilevs and Hughes, 2007). Adaptively refined quadrature rules are used to faithfully capture the flow domain geometry in the discrete problem without modifying the non-boundary-fitted background mesh. It was found by Xu et al. (2016) that the faithful representation of the geometry in intersected elements is critical for accurate immersogeometric fluid flow analysis.

To simulate fluid flow past B-rep CAD models using the immersogeometric method, two key geometric operations need to be performed. The first is to evaluate points on the surface of the solid model to enforce Dirichlet boundary conditions. The second is to perform point membership classification on the points belonging to the background mesh to identify points inside the solid CAD model. Both operations need to be performed adaptively for the CFD analysis to be accurate and converged. In this paper, we have developed new methods to perform these operations directly using the B-rep of the CAD model.