IGA in CFD and FSI: Refinement Strategies, AI Integration, and Future Directions

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Abstract. Isogeometric Analysis (IGA), introduced by Hughes et al. in 2005, seamlessly integrates CAD and FEA by directly utilizing NURBS, T-Splines, and Subdivision Surfaces in numerical simulations. This approach eliminates geometric approximation errors while enhancing computational efficiency. This review examines key developments in fluid-structure interaction, turbulence modeling, and AI-driven optimization, highlighting innovations such as Snakes Isogeometric Analysis for respiratory modeling, VMS-enhanced Navier-Stokes solvers, and THB-spline adaptive refinement for complex flows. Recent applications include extreme cases like Underwater Explosion FSI and the integration of Graph Neural Networks for topology optimization. With its continued development, IGA is emerging as a key framework in computational science driving innovation in high accuracy simulations and facilitating the integration of AI informed numerical techniques.

Keywords: IGA, FEA, CAD, geometric errors, FSI, SIGA, Navier-Stokes solvers.

1 Introduction

Isogeometric Analysis (IGA) firstly introduced in 2005 by professor Tomas JP Hughes [1] as a new computational approach designed to minimize the gap between Computer-Aided Design (CAD) and Finite Element Analysis (FEA). Finite Element Method (FEM), mostly require mesh generation and geometric simplifications, which can introduce errors and inefficiencies [2].[3]. In contrast, IGA directly incorporates precise geometric representations from CAD, such as Non-Uniform Rational B-Splines (NURBS), T-Splines, and Subdivision Surfaces, into the simulation process. This approach removes the necessity for geometry conversion, thereby enabling a more streamlined and precise analytical framework.

Over the past several years, IGA has garnered widespread recognition across both academic research and industry applications, driving notable progress in fields such as structural mechanics [4], fluid dynamics [5], [6], electromagnetics[7], and biomechanics [8]. Researchers have introduced various refinement techniques, including h-, p-, and k-refinement [9], which substantially enhance simulation efficiency. These advancements have proven especially valuable in addressing complex problems, particularly those involving fluid-structure interactions (FSI) and high-order partial differential equations (PDEs) topics that constitute the primary focus of this comprehensive review.

2 Early Foundations and Evolution of Isogeometric Analysis in CFD

2.1 Early Advances in IGA for CFD and Hydrodynamic Modeling

Between 1997 and 2011, research on IGA in hydrodynamics and computational fluid dynamics was in its early stages. Foundational studies began in 1997 with the introduction of stabilization techniques designed for fluid flow problems. Although these initial investigations did not explicitly identify with IGA, they established essential principles that shaped the field's future development. Over time, new applications emerged, especially involving FSI, the mutual interaction between fluid flow and deformable structures with electro-rheological fluids, smart materials whose viscosity varies in response to electric fields. These materials contributed to advances in microfluidic devices and vibration control systems that remain relevant today. A significant milestone occurred in 2011 with the integration of harmonic mapping methods into IGA, enhancing the ability to model smooth domain deformations necessary for accurately simulating fluid interactions with moving boundaries. This advancement attracted considerable interest in engineering fields, particularly for shape optimization and dynamic simulations. The same year, the introduction of truncated basis functions represented a fundamental shift in mesh refinement strategies, paving the way for hierarchical B-splines mathematical functions enabling efficient and adaptive geometry representation and substantially improving computational efficiency. By 2014, visualization methods had progressed alongside mathematical innovations, enabling three-dimensional rendering of complex flow features such as vorticity and temperature fields. Together, these developments laid a solid foundation for modern applications of IGA in fluid dynamics, transforming it into a versatile and powerful tool for addressing intricate fluid flow challenges.

2.2 From Concept to Revolution: How Professor T.J.P Hughes and His Team Shaped Isogeometric Analysis

Since its introduction by Hughes et al. [1], Isogeometric Analysis (IGA) has significantly transformed computational modeling by unifying the traditionally separate domains of computer-aided design (CAD) and finite element analysis (FEA). Conventional FEA typically relies on polygonal approximations of CAD geometries, which can lead to geometric inaccuracies and meshing inefficiencies. In contrast, IGA utilizes exact geometric representations through non-uniform rational B-splines (NURBS), T-splines, and subdivision surfaces, thereby preserving the fidelity of the original geometry throughout the analysis process. The development of hierarchical refinement techniques namely h-refinement (element subdivision), p-refinement (increasing polynomial order), and k-refinement (elevating both polynomial degree and continuity) has further enhanced the method's flexibility, enabling higher numerical precision and improved computational efficiency. These advancements have established IGA as a robust and versatile alternative to conventional finite element methods, with demonstrated advantages in structural mechanics, fluid dynamics, and biomedical engineering.

Building upon these early foundations, the field underwent a pivotal transformation as research efforts increasingly concentrated on formalizing the direct integration of CAD and FEA. A landmark moment in this progression was the seminal work by Hughes and colleagues, which laid the groundwork for a unified geometric and analytical framework that continues to shape the evolution of IGA methodologies [14]. Far more than a conventional academic paper, this work served as a comprehensive roadmap for modernizing computational engineering. Its significance lies in the authors' systematic and well-articulated framework for embedding IGA within existing numerical methodologies, rather than advocating for a complete overhaul of existing systems, Hughes and his team demonstrated how IGA could seamlessly augment and enhance established computational methodologies. The influence of this work rapidly extended across various high-precision industries. In the automotive sector, engineers recognized the potential to optimize complex aerodynamic surfaces while preserving geometric fidelity. Aerospace designers benefited from the ability to analyze intricate structural components with exceptional accuracy. Similarly, naval architects leveraged IGA to simulate hull hydrodynamics with a high degree of precision achieving these advancements without compromising the exact geometry defined by the original CAD models.

Arguably the most consequential practical advancement introduced by IGA is the elimination of the labor-intensive meshing process, which has historically represented a significant bottleneck between design and analysis phases. By maintaining high-order continuity throughout the computational workflow, IGA facilitates a direct and accurate transition from geometric modeling to performance evaluation. This seamless integration not only accelerates the overall design and development cycle but also opens new avenues for innovation in advanced engineering and product design.

A significant advancement in computational fluid dynamics emerged when researchers began leveraging IGA to address one of the most complex challenges in biomedical engineering: accurately modeling blood flow within the human cardiovascular system. A pivotal study published in 2020 [15] marked a departure from incremental progress, offering a genuine breakthrough in the simulation of cardiovascular dynamics. This achievement was largely attributed to the innovative integration of Variational Multi-Level methods (VMLM) with Arbitrary Lagrangian–Eulerian formulations within an isogeometric framework. Traditional computational techniques had long struggled to replicate the pulsatile and highly nonlinear nature of blood flow, particularly around intricate anatomical structures such as heart valves. However, this unified approach demonstrated an unprecedented capacity to capture these interactions with high fidelity.

The human heart, characterized by its irregular geometry and continuous motion, had historically posed a formidable challenge to precise computational modeling a challenge that this methodology successfully began to overcome. IGA's ability to maintain smooth, anatomically accurate representations throughout the simulation process proved to be the missing piece. Suddenly, researchers could notice virtual blood cells navigating through arteries and around valve leaflets with unprecedented detail opening new windows into understanding cardiovascular disease.

By 2021, research efforts increasingly turned toward addressing a longstanding computational challenge: maintaining mathematical continuity across complex multi-patch domains. A pivotal contribution in this area was presented in a comprehensive chapter [16], which introduced three innovative approaches that redefined how detailed geometries are managed within the isogeometric framework. These strategies were not merely theoretical in nature; their practical effectiveness was convincingly demonstrated by Guendaoui and colleagues [17], as illustrated in Figure 1 of their study. The implications of this advancement extended far beyond biomedical applications. In aerospace engineering, the improved continuity enabled more accurate modeling of airflow around intricate wing structures. In materials science, it provided deeper insights into fracture mechanics of composite materials under stress. In advanced manufacturing, it offered new avenues for optimizing additive manufacturing processes, particularly in the fabrication of complex geometries. What began as a specialized numerical technique had, by this point, evolved into a powerful and adaptable computational toolkit reshaping how researchers and engineers interpret and engage with the physical world.

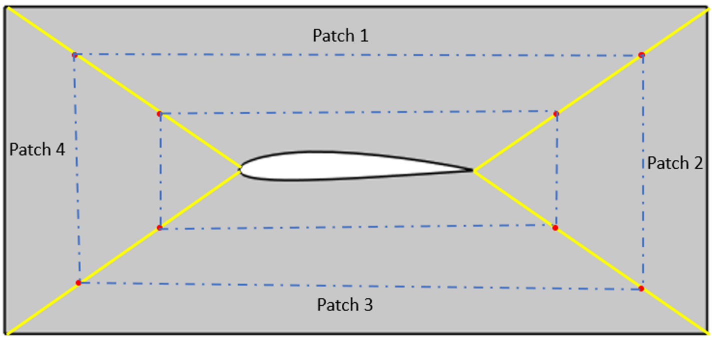

Fig. 1. Multi-patch Domain of the Airfoil NACA2412 [17].

IGA's remarkable journey continued when researchers applied it to the intricate world of biomechanical simulation. The 2021 study [16] on ankle joint mechanics wasn't just another paper it demonstrated something orthopedic specialists had been seeking for years: a computational method that could truly capture the complex interplay of bones, cartilage, and ligaments without oversimplification. Traditional finite element methods had always struggled with the ankle's intricate geometry and multi-directional ligament structures. Engineers were forced to make geometric compromises that eventually affected simulation accuracy. IGA changed the game by preserving anatomical details that would previously have been smoothed away or approximated. The results were striking. When researchers compared force transfer patterns between IGA and conventional approaches, they found significantly more realistic load allocation across joint surfaces. This wasn't merely an academic improvement it translated directly to better predictions of joint wear, injury risk, and prosthetic performance. Orthopedic surgeons quickly identified the potential. With more accurate simulations, they could better plan complex procedures, design custom implants, and predict patient-specific outcomes. Prosthetists gained new tools for creating replacement joints that more faithfully replicated natural biomechanics. Over two decades, what began as a specialized numerical approach has transformed into something far more significant a computational stand between design and analysis that preserves the geometric integrity fundamental to engineering performance. IGA's ability to maintain exact geometries while providing higher-order continuity has revolutionized how we approach complex simulations across disciplines. The frontier of IGA research now extends into turbulence modeling, where its smooth basis functions capture complex fluid behaviors with fewer computational resources. Researchers are developing innovative multi-patch techniques to handle increasingly complex geometries, while others explore hybrid approaches that combine IGA's advantages with complementary methods. As we'll see in the following sections, IGA's integration with computational fluid dynamics, multiphysics simulations, and emerging AI optimization techniques is introducing new horizons in engineering analysis that were barely imaginable when this journey began.

2.3 Expanding Horizons: The Growing Impact of Isogeometric Analysis in Biomedical Engineering, Flow Modeling, and AI-Driven Optimization

IGA has increasingly emerged as a transformative computational framework, effectively bridging the gap between traditional FEM and the geometric precision provided by CAD. Recent advancements have extended its applications into fields such as biomedical engineering, flow analysis, and AI-driven topology optimization, demonstrating its versatility in addressing complex numerical challenges. In medical simulation, IGA has proven particularly effective in enhancing the accuracy of patient-specific modeling and predictive analysis. Ortiz-Puerta et al. [18] introduced SIGA, a novel method for constructing highly accurate airway models from medical images, which outperforms conventional surface-fitting techniques—particularly in handling complex, non-convex airway geometries. Based on the variational formulation of the Snakes segmentation problem, SIGA ensures precise surface representation of respiratory structures, making it an invaluable tool for flow simulations in pulmonary diagnostics and infection modeling.

Similarly, Torre et al. [19] explored its use in heart modeling, focusing on hemodynamics, valve mechanics, and cardiac tissue dynamics, highlighting how it enables seamless geometric representation and numerical stability in simulating FSI within the heart, eventually improving virtual testing of medical devices and treatment strategies. Beyond biomedical applications, it has seen significant adoption in flow modeling, particularly in the study of multiphase interactions, turbulence, and highspeed FSI. Takizawa et al. [6] provided a comprehensive overview of Navier-Stokes solvers, detailing their advantages in handling turbulent and unsteady flows across a range of engineering applications while emphasizing the role of stabilized and VMS methods in ensuring numerical stability and accuracy for both incompressible and compressible cases.

In the context of adaptive mesh refinement, Divi et al. [20] proposed a residual-based error estimation approach, utilizing THB-splines (Truncated Hierarchical B-Splines) for local mesh refinement see figure 3, substantially improving the precision of heat conduction and viscous computations.

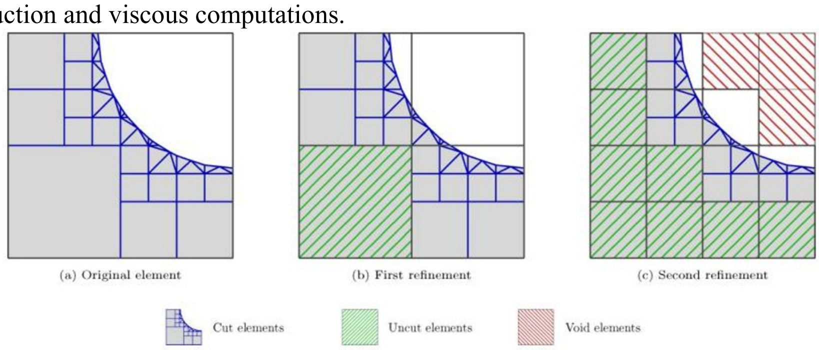

Fig. 2. Error Estimation of Residual-based and adaptivity for stabilized immersed IGA using THB-splines [20]

while Yu et al. [21] applied it to spilling simulations in partially filled tanks, introducing a mass correction algorithm to enhance liquid-gas interface tracking see figure 3, demonstrating superior accuracy compared to conventional techniques. A particularly demanding area of flow-structure modeling is FSI under extreme conditions, such as UNDEX-FSI (Underwater Explosion Fluid-Structure Interaction) and impact analysis, where Shende et al. [22] introduced an immersed method for simulating pressure wave propagation through thin-shell structures, validated back to experimental data, proving its effectiveness in predicting structural response to blast loads.

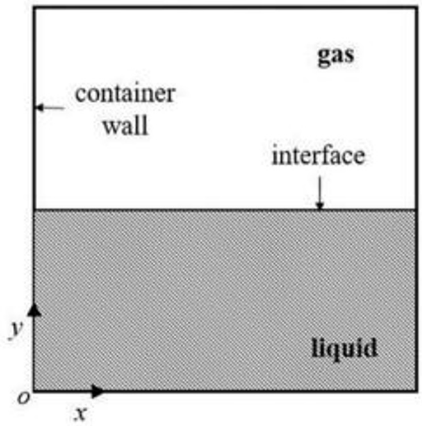

Fig. 3. Rectangular container partially filled with liquid [21].

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Finally, Zhong et al. [23] explored the fusion of GNNs (Graph Neural Networks) for topology optimization, demonstrating superior accuracy in handling complex boundary conditions and geometry-consistent optimizations, offering a promising direction for data-driven computational design. By leveraging ResNetV2 and Point Transformer architectures, their model effectively outperformed traditional CNN-based datasets (Convolutional Neural Networks Based dataset), paving the way for AI-driven mesh adaptation and shape optimization in engineering simulations.

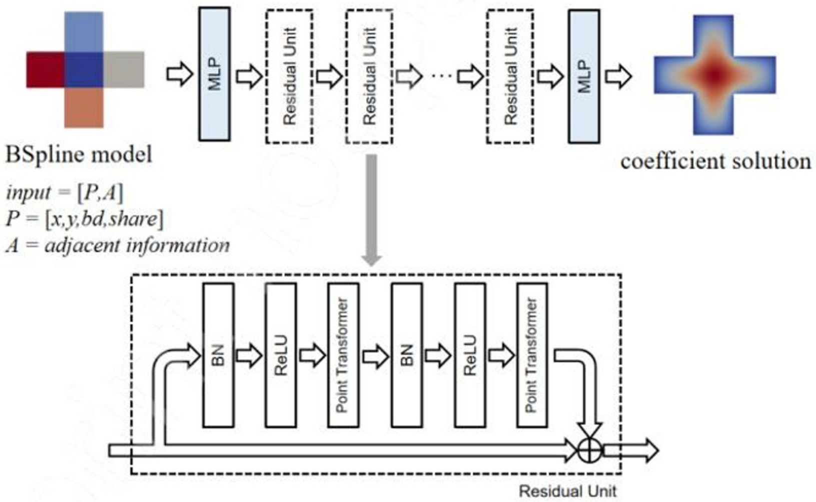

Fig.4. ResNetV2 Network architecture [23]

ResNetV2 builds upon the foundational ideas of residual learning introduced in its predecessor by structuring each block such that all transformations occur within the residual pathway. Leveraging this design, PointTransformer layers are integrated to strengthen the network's ability to approximate solutions to PDE, particularly in capturing intricate spatial dependencies. particularly in capturing intricate spatial dependencies. offering improved representation learning for complex spatial structures. The PointTransformer layer improves local feature resilience, while ResNetV2 ensures unimpeded forward and backward propagation, mitigating the effects of non-linear transformations. This combination allows for better information flow, reducing issues like over optimizing and over-smoothing, ultimately leading to a more robust and accurate model.

These recent advancements highlight its growing impact across multiple disciplines, from biomedical engineering and flow analysis to AI-driven computational mechanics, solidifying its role as a cornerstone technology in high-fidelity simulation frameworks. As research continues to refine adaptive mesh techniques, turbulence modeling, and AI-enhanced numerical methods, future developments will focus on stabilized techniques, VMS methods, and hybrid computational approaches for enhanced performance in real-world applications.

3 Conclusion

Reflecting on IGA's achievements so far, it is apparent that alongside the advances in technology, the new breakthrough in Computational Science is quite notable. Initially, there existed only a new innovative approach for resolving problems numerically, which later transformed into a solution that finally links efficiently design and analysis. By eliminating the unilateral boundary between CAD and FEA, IGA hasn't just added capabilities it has changed the pattern of how engineers tackle complex issues. The limitations and simplifications made to structures are no longer necessary as they can now be analyzed in their true geometric complexity. At the former time impossible accurate simulations of fluid flows have now been made exhibitable with unmatched precision. Biomechanical systems that were approximated can now be modeled anatomically exact. The incorporation of AI-powered optimization techniques is, without a doubt, the most promising frontier. Unlike traditional methods, these technologies do not simply automate processes; rather, they redefine design automation and open up countless possibilities that human designers would not think of. Adaptive mesh refinement methodologies have shifted the focus of distributing computational hands power, directing it to where it's most crucial. IGA's reach is broader than just academic research; it is beyond the educational realm and encompasses all of practical life. Outcomes like more fuel-efficient vehicles, safer buildings, and advanced medic
back at IGA's remarkable journey, it's clear that the emergence of something truly special in computational science observed. What began as an innovative numerical approach has matured into a transformative tool that finally bridges the long-standing divide between design and analysis. By eliminating the artificial barrier between CAD and FEA, IGA has not just incremented existing capabilities—it has fundamentally changed how engineers approach complex problems. Structures that once needed simplification can now be analyzed in their full geometric complexity. Fluid flows that defied accurate simulation are now rendered with unprecedented fidelity. Biomechanical systems that were once approximated are now modeled with anatomical precision. The integration of AI-driven optimization methods represents perhaps the most exciting frontier. These techniques aren't merely automating existing processes they're detecting design possibilities that human engineers might never have considered. Adaptive mesh refinement strategies have transformed how computational resources are allocated, focusing power precisely where it's needed most. As IGA continues to evolve, its impact extends far beyond academic research into practical applications that touch our daily lives. More efficient vehicles, safer buildings, more effective medical devices, and countless other innovations owe their performance to this computational approach. The future looks notably promising as researchers continue refining IGA methodologies. What we're witnessing isn't just another computational tool it's a fundamental shift in how we understand and interact with the physical world through simulation. IGA has earned its place not just as a current solution but as a foundation for the next generation of computational science.

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