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ISOGEOMETRIC FEM/BEM APPROACH FOR A COUPLED ACOUSTIC FLUID-STRUCTURAL INTERACTION SYSTEMS

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ABSTRACT

In the present work, an isogeometric approach is proposed to address the acoustic-structural coupled system, which is essential for noise control analysis of thin and light weight shell structures instead of dealing with sound hard structures. The acoustic model is based on the time-harmonic Helmholtz equation for wave propagation problems and analyzed by isogeometric boundary element analysis, while the structural model is analyzed by an isogeometric Reissner-Mindlin shell formulation following the finite element basis. A direct approach is performed to couple both the boundary element and finite element models, thus benefitting from using the same isogeometric mesh. The isogeometric analysis is proposed for both models as it has the ability to model real geometries by adopting moderate degrees of freedom. This will enable us to further analyze large-scale problems or irregular complex geometries such as vibroacoustic metamaterials

Keywords: *BEM, FEM, IGA, shells, acoustics*

1. INTRODUCTION

The interaction between vibrating structures and surrounding fluids is a fundamental aspect in the design and performance of submarines, aircraft, and automobiles. Specifically, thin structures immersed in dense fluids require precise evaluation of their dynamic responses to acoustic pressure. This concept is particularly significant in the field of vibroacoustic metamaterials, where achieving an optimal interaction between fluid dynamics and structural behavior is essential.

A major challenge in computational acoustics lies in the accurate simulation of complex geometries while maintaining high continuity. Traditional numerical approaches necessitate highly refined meshes to capture intricate geometric details, leading to excessive computational costs that make large-scale simulations inefficient.

To overcome these limitations, this study introduces an advanced acoustic model based on the Helmholtz wave propagation equation, solved through isogeometric boundary element analysis. Simultaneously, the structural behavior is formulated using an isogeometric Reissner-Mindlin shell approach, with both models seamlessly integrated via an isogeometric direct coupling methodology.

2. ISOGEOMETRIC ANALYSIS (IGA)

Isogeometric Analysis (IGA) [1] is an innovative computational technique that bridges Computer-Aided Design (CAD) and numerical simulation. Its primary advantage lies in its ability to represent exact and intricate geometries, providing an accurate depiction of real-world structures. Unlike conventional numerical techniques, IGA utilizes the same basis functions to define the CAD model and approximate physical variables, ensuring a direct and consistent representation between geometry and analysis.

Another key benefit of IGA is its capacity for efficient refinement while maintaining high continuity. This characteristic is particularly valuable in acoustic simulations, where capturing detailed geometries and wave propagation effects is critical. Additionally, IGA minimizes the pollution error commonly encountered in traditional numerical methods when solving acoustic problems, ensuring consistent solution quality across different scales and frequencies.

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Overall, IGA delivers superior accuracy even with relatively coarse meshes compared to conventional approaches. Its ability to handle complex geometries with efficiency makes it a powerful tool for a broad range of engineering applications.

3. IGABEM FOR HELMHOLTZ WAVE PROPAGATION SCATTERING PROBLEMS

The Boundary Element Method (BEM) is widely recognized as a robust numerical tool, particularly suited for acoustic problems involving infinite or unbounded domains. Unlike domain-based techniques, BEM operates directly on boundaries, eliminating the need for artificial truncation surfaces—an advantage when modeling open or semi-infinite spaces. This property makes BEM particularly effective for solving the Helmholtz equation in acoustics, which frequently involves infinite domains, such as underwater or open-air environments [2].
A major advantage of BEM is its ability to reduce problem dimensionality, transforming a three-dimensional problem into a two-dimensional one, significantly decreasing computational effort. When combined with Isogeometric Analysis (IGA), BEM becomes even more effective, as IGA naturally integrates CAD-based geometrical models to define boundaries [3]. This seamless combination enhances accuracy and efficiency in solving complex acoustic problems, outperforming standard BEM in various applications [4,5].
Furthermore, BEM inherently satisfies the Sommerfeld radiation condition, which is crucial for accurately modeling wave behavior in open domains [6]. This automatic fulfillment of boundary conditions at infinity simplifies problem formulation, improving computational reliability. As applied to the Helmholtz equation, IGABEM offers a highly effective strategy for addressing acoustic problems in unbounded domains with intricate geometries.

4. ISOGEOMETRIC ANALYSIS FOR REISSNER-MINDLIN SHELLS

The Isogeometric Reissner-Mindlin shell formulation provides an advanced numerical approach for modeling thin, curved structures [7]. This method represents a specialized variant of three-dimensional solid elements with small thickness, making it highly effective for thin-walled structures. Unlike conventional 3D finite element models, which can be computationally demanding and susceptible to conditioning issues, the IGA-based Reissner-Mindlin shell approach reduces problem complexity while preserving solution accuracy.
In this formulation, the shell's mid-surface is discretized using a two-dimensional isogeometric representation, ensuring smooth and continuous modeling, while the thickness dimension is interpolated using linear Lagrange basis functions. This hybrid technique allows IGA to accurately capture geometric details with high continuity, producing precise results even with relatively coarse meshes. As a result, IGA-based Reissner-Mindlin shells offer improved computational efficiency and enhanced accuracy, making them highly suitable for complex structural analyses.

5. ACOUSTIC-STRUCTURAL COUPLING SYSTEMS

Traditional computational techniques, such as the Finite Element Method (FEM) and the Boundary Element Method (BEM), often employ different mesh types—typically triangular or quadrilateral—for structural and acoustic domains [8]. This inconsistency poses challenges at the coupling interface between these two domains. To resolve this issue, conventional methods rely on additional techniques, such as defining new intersecting elements or projecting one mesh onto another [9]. While effective, these strategies introduce complexity and increase computational demands.
IGA addresses these challenges by ensuring identical meshes for both IGABEM and IGAFEM at the coupling interface. This uniformity simplifies the coupling process by maintaining consistent normal directions and basis functions across both domains. Consequently, the computation of coupling matrices becomes more straightforward and efficient. By facilitating a seamless integration between structural and acoustic analyses, IGA-based coupling systems enhance both computational efficiency and solution accuracy.

6. DISCUSSION

Isogeometric Analysis (IGA) has demonstrated its effectiveness in both the Finite Element Method (FEM) and the Boundary Element Method (BEM), offering significant advantages over traditional numerical approaches. One of its major strengths is its ability to deliver high accuracy while preserving exact geometric representations, even when using coarser meshes. This represents a substantial improvement over conventional methods, which typically

require fine meshes to achieve similar levels of precision. By reducing the dependency on highly refined meshes, IGA enhances computational efficiency without sacrificing accuracy, making it particularly valuable for solving complex problems in acoustics and structural mechanics.
Another notable advantage of IGA is its ability to seamlessly integrate FEM and BEM models. This capability is crucial when analyzing systems that involve interactions between structural and acoustic domains. By maintaining consistent meshes and basis functions across both domains, IGA simplifies the coupling process, reducing errors and increasing efficiency. This is especially beneficial in applications requiring precise modeling of vibroacoustic interactions.
Moreover, the properties of the surrounding fluid, such as density, significantly impact the coupling effect between structural and acoustic domains. As fluid density increases, the interaction between the structure and the fluid becomes more pronounced, influencing the system's overall response. This is particularly relevant in underwater acoustics, where fluid density is considerably higher than in air, leading to more significant vibroacoustic effects, such as resonances and energy transfer. Accurately capturing these interactions is critical for optimizing engineering designs and achieving reliable simulations.

7. CONCLUSION

In summary, IGA provides an efficient and accurate framework for coupling FEM and BEM models, enabling precise simulations of complex acoustic-structural interactions. Its ability to maintain accuracy with coarser meshes and simplify coupling procedures makes it an invaluable tool for addressing multi-domain problems. Additionally, considering fluid properties such as density is essential for accurately modeling coupling effects and optimizing system performance.
Another key objective of this study is to model intricate and irregular geometries using IGA as a foundational step toward accurately simulating metamaterials. The proposed approach aims to achieve higher accuracy than traditional numerical methods while utilizing a moderate number of degrees of freedom, ensuring computational efficiency and precision.

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