REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 03-08-2023	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 2-Apr-2021 - 1-Apr-2023

4. TITLE AND SUBTITLE Final Report: Isogeometric Analysis Methods for High Fidelity Mobility Applications	5a. CONTRACT NUMBER
	5b. GRANT NUMBER W911NF-21-C-0030
	5c. PROGRAM ELEMENT NUMBER 665502
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES YB Numerics Inc. 157 Waterman St. APT 7 Providence, RI 02906 -0000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 78476-WS-ST2.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Yuri Bazilevs
UU	UU	UU	UU		19b. TELEPHONE NUMBER 512-799-6235

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 26-Sep-2023

Agency Code: 21XD

Proposal Number: 78476WSST2 **Agreement Number: W911NF-21-C-0030**

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Report Date: 01-May-2023 Date Received: 03-Aug-2023
Final Report for Period Beginning 02-Apr-2021 and Ending 01-Apr-2023
Title: Isogeometric Analysis Methods for High Fidelity Mobility Applications
Begin Performance Period: 02-Apr-2021 **End Performance Period:** 01-Apr-2023
Report Term: 0-Other
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: Isogeometric Analysis (IGA) is a next-generation computational method that provides superior accuracy and high-fidelity computational analysis solutions. IGA, because of its special higher-order nature, has several very desirable features in multiscale computation of flow and fluid–structure interaction (FSI) problems that are ubiquitous in mobility applications.

Every computational analysis starts with a suitable definition of the problem geometry followed by mesh generation for that geometry. However, mesh generation in IGA, such as Non-Uniform Rational B-Spline (NURBS) meshes generation, is not as established and straightforward as mesh generation in the standard discretization methods such as Finite Difference (FD) and Finite Element (FE) methods. To make IGA-based flow and FSI computations even more powerful and more practical, the mesh generation must be less arduous, more straightforward, more automated, and basically as established as it is now for the FD and FE methods.

This Phase II project major technical goal is to remove this impediment to widespread IGA use in real-world computational flow and FSI analysis. It is envisioned that IGA-based computations will play a more significant role in supporting problem solving and design in military and commercial applications and will help bring multiscale computational flow and FSI analysis to a new level where it can make a much bigger impact.

The Phase II project another major goal is to begin dissemination and marketing of the results to industry, lab and academic collaborators/partners. This activity presents the first steps toward commercialization of the technology developed in this project.

Accomplishments: We developed a meshing pipeline that is built on Pointwise software (or other software package with similar capabilities) as the base platform. This approach is suitable for the “analysis heavy” user that has good familiarity with mesh generation software and wishes to expand his/her arsenal of computational tools to include IGA.

We carried out extensive benchmarking and performance assessment of our method. We considered two test cases: a unit cube and a shell structure modeled as a solid object. The latter geometry was provided by Dassault Systemes Simulia in the STEP file format. In each test case, we carried out a linear structural vibrations analysis and examine the convergence of the natural frequencies under mesh refinement. Accurate representation of the structural vibration modes is an indicator of the overall accuracy of a numerical method in structural mechanics. In the context of FSI, coupling with complex unsteady flows may trigger a structural response that activates the entire spectrum of the structural vibration modes. As a result, the structural discretization method that is accurate and robust across the entire spectrum, and not just in the low modes, will likely produce a more accurate FSI response. We clearly demonstrated that IGA based on NURBS is indeed accurate and robust across the entire spectrum.

We carried out extensive demonstrations of out meshing capabilities using geometrically and structurally complex examples, some of which were provided by industry. In particular: 1. We carried out structural vibrations analyses (with mesh convergence studies!) for a nuclear reactor pressure vessel; 2. We carried out computations of a car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation.

For more detailed description of the Phase II accomplishments see the *.pdf document in the "Upload" section.

Training Opportunities: Nothing to Report

Results Dissemination: We developed a five-part video tutorial with high quality video and sound explaining the NURBS mesh generation process. The goal of the video tutorial is to clearly show the steps of the process to generate IGA meshes using the methods, algorithms, codes, and tools developed and used in this PhaseII project. The material in the tutorial is presented in a manner that will enable the users to follow the steps and create their own geometry models and IGA meshes for a variety of analyses.

We published several papers (see References below) and delivered technical presentations at scientific conferences based on the work and results generated as part of this STTR project.

To introduce industry and labs to our meshing methods and tools, the YBN team visited Dassault Systemes Simulia Inc. in Johnston, RI. The YBN team made a presentation to several teams working on ABAQUS Software development on the recent advances in IGA, devoting a significant portion of the presentation to showcasing the NURBS meshing techniques developed in this project and the superior performance of IGA for structural vibrations.

The RUWU and YBN teams started a “test user” collaboration with the Computational Fluid and Structural Mechanics group at the University of Calgary. The U Calgary group, with guidance from the RUWU and YBN teams, are now using the NURBS mesh generation tools that are being developed in the STTR project. This will be a case of practical use of the mesh generation tools by those outside the RUWU and YBN teams. Lessons learned from this collaboration will help us improve the wider usability of the tools. The collaboration with the U Calgary group is on the simulation of compressible flows. We focused on a problem of 3D compressible transonic flow over the ONERA M6 wing. NURBS meshing in this case made use of an external CAD file that defined the wing surfaces and the bounding domain.

The NURBS meshing software is being used at Takizawa Lab at Waseda University (Japan) in an applied research project in collaboration with ISUZU Motors. The project is focusing on flow analysis in an exhaust pipe, including the diesel oxidation catalyst (DOC) and diesel particulate filter. Estimating the clogging of the DOC cell openings caused by soot piling is one of the practical objectives of the project. This is a good example of how the NURBS meshing software is directly contributing to a real-world simulation that is important to industry.

For more detailed description of the Phase II dissemination see the *.pdf document in the "Upload" section.

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Journal Papers

T. Kuraishi, S. Yamasaki, K. Takizawa, T.E. Tezduyar, Z. Xu and R. Kaneko, “Space-Time Isogeometric Analysis of Car and Tire Aerodynamics with Road Contact and Tire Deformation and Rotation”, Computational Mechanics, 70 (2022) 49-72.

T. Kuraishi, T. Terahara, K. Takizawa and T.E. Tezduyar, “Computational Flow Analysis with Boundary Layer and Contact Representation: I. Tire Aerodynamics with Road Contact”, Journal of Mechanics, 38 (2022) 77-87.

Y. Liu, K. Takizawa, Y. Otoguro, T. Kuraishi and T.E. Tezduyar, “Flow Computation with the Space-Time Isogeometric Analysis and Higher-Order Basis Functions in Time”, Mathematical Models and Methods in Applied Sciences, 32 (2022) 2445-2475.

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T. Kuraishi, Z. Xu, K. Takizawa, T.E. Tezduyar and S. Yamasaki, “High-Resolution Multi-Domain Space-Time Isogeometric Analysis of Car and Tire Aerodynamics with Road Contact and Tire Deformation and Rotation”, Computational Mechanics, 70 (2022) 1257-1279.

Y. Liu, K. Takizawa, T.E. Tezduyar, T. Kuraishi and Y. Zhang, “Carrier-Domain Method for High-Resolution Computation of Time-Periodic Long-Wake Flows”, Computational Mechanics, 71 (2022) 169-190.

Book Chapters

E. Wobbes, Y. Bazilevs, T. Kuraishi, Y. Otoguro, K. Takizawa and T.E. Tezduyar, “Advanced IGA Mesh Generation and Application to Structural Vibrations”, In Frontiers in Computational Fluid-Structure Interaction and Flow Simulation, Birkhäuser, Cham, 2023.

T. Kuraishi, K. Takizawa, T.E. Tezduyar, Z. Xu, S. Yamasaki and R. Kaneko “Multiscale Space-Time Isogeometric Analysis of Car and Tire Aerodynamics with Road Contact and Tire Deformation: Full-Domain Computation to High-Resolution Tire-Domain Computations”, to appear in a special volume to be published by Springer (2022).

Honors and Awards: Received by Y. Bazilevs
2021 ASME Materials Division Centennial Mid-Career Award
2021 Distinguished Public Lecture, Civil Engineering, University of Hong Kong
2021 Distinguished Lecture, Mechanical and Aerospace Engineering, George Washington U
2022 International Association for Computational Mechanics (IACM) Computational Mechanics Award
2022 Journal of Mechanics Best Paper Award

Received by T. Tezduyar
2021 Honorary Member, Japan Association for Computational Mechanics
2023 John von Neumann Medal, US Association for Computational Mechanics

Protocol Activity Status:

Technology Transfer: The YB Numerics (YBN) and the Rice University-Waseda University (RUWU) teams met with researchers from the ARL Vehicles Technology Directorate (ARL-VTD) to discuss the application of NURBS meshing methods to hypersonic applications. The YBN team made a presentation to the ARL-VTD researchers on the meshing tools in support of IGA simulations.

PARTICIPANTS:

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Project Contribution:
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1 Motivation

The designs of US Army vehicles, such as the Abrams tank and Apache and Black Hawk helicopters, are continuously improved to deliver increased performance on the battlefield. These vehicles are costly to build and maintain, and, as a result, optimal performance and operational reliability become the key aspects of the vehicle design in mobility applications. As the vehicle and engine designs get more sophisticated, the corresponding computational analysis methods must also mature to support advances in the mobility technology of the US military and beyond. Same is true for many commercial applications, such as energy, transportation, and medicine, that could greatly benefit from mature computational analysis methods.

Isogeometric Analysis (IGA) is a next-generation computational method that provides superior accuracy and high-fidelity computational analysis solutions. IGA, because of its special higher-order nature, has several very desirable features in multiscale computation of flow and fluid–structure interaction (FSI) problems that are ubiquitous in mobility applications.

Every computational analysis starts with a suitable definition of the problem geometry followed by mesh generation for that geometry. However, mesh generation in IGA, such as Non-Uniform Rational B-Spline (NURBS) meshes generation, is not as established and straightforward as mesh generation in the standard discretization methods such as Finite Difference (FD) and Finite Element (FE) methods. To make IGA-based flow and FSI computations even more powerful and more practical, the mesh generation must be less arduous, more straightforward, more automated, and basically as established as it is now for the FD and FE methods.

This Phase II project is focused on removing this impediment to widespread IGA use in real-world computational flow and FSI analysis. It is envisioned that IGA-based computations will play a more significant role in supporting problem solving and design in military and commercial applications and will help bring multiscale computational flow and FSI analysis to a new level where it can make a much bigger impact.

2 Technical Achievements

2.1 *Overview of the NURBS Meshing Methodology*

We focused on developing a meshing pipeline that is built on Pointwise software (or other software package with similar capabilities) as the base platform. This approach is suitable for the "analysis heavy" user that has good familiarity with mesh generation software and wishes to expand his/her arsenal of computational tools to include IGA.

As a first step of the NURBS meshing pipeline, we assume that the block-structured mesh we start with is the outcome of the application of Pointwise software and is of high quality. The mesh consists of trilinear elements, and we see each block as a precursor to a NURBS patch.

The second step involves several projections. For those projections, we define a common parametric space between each block and the corresponding NURBS patch. We choose the parametric space for each patch to be a unit cube. Values in the knot vector may be distributed in a uniform fashion. Alternatively, knots may be placed such that their spacing is proportional to the spacing of the physical nodes. In the latter, the gradients show essentially a linear variation within the elements, which will result in more accurate evaluation of the integrals by means of numerical quadrature. Since the knot vectors are defined in each patch in a multi-dimensional context, to obtain the element lengths in each direction, averaging needs to be performed in the other two directions.

Once the knot vectors are computed, projection operations are carried out to find the control-point locations on the patch. For each patch, the projections are done hierarchically. First the control points at the corners of the patch are set to the same locations as the corner grid points of the block. Then the edges between the parch corners are projected by using the common parametric space. Next, the surfaces between the patch edges are projected, and the sequence is completed with the projection of the volumes between the patch surfaces. For two adjacent blocks, the projections described above result in the same control-point positions over the surface they share, provided that the two blocks have the same knot vectors over the shared surface. This happens automatically for uniform knot spacing. To make it happen in the physical-space proportional spacing, the requirement of matching knot vectors is considered while doing the element length averaging. The control-point variables are declared to be the same between the adjacent patches over the shared surface, which results in C^0 continuity for the basis function across the surface.

Additional techniques are implemented to enable the user to reduce the number of elements in each block by a desired factor and to ensure that a given edge or surface coincides with the exact model edge or surface. The latter provides the important link with the original CAD geometry, which is one of the distinguishing features of IGA.

In the third step, the resulting NURBS meshes are converted to the Bezier extraction representation, which facilitates the integration of IGA into traditional FE software. The Bezier extraction representation is then read into an FE-style solver to carry out the analysis of choice (e.g., fluid mechanics, structural mechanics or FSI).

2.1.1 *Mesh Inspection*

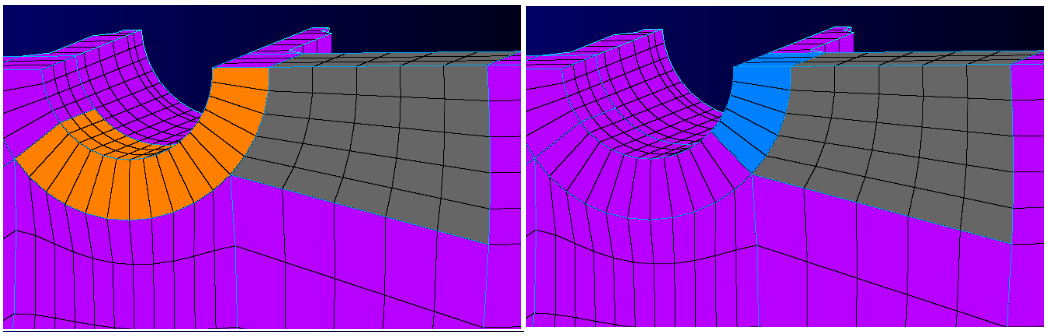

(a) (b)

Figure 1. Multi-block decomposition leading to: (a) Non-conforming NURBS mesh; (b) Conforming NURBS mesh.

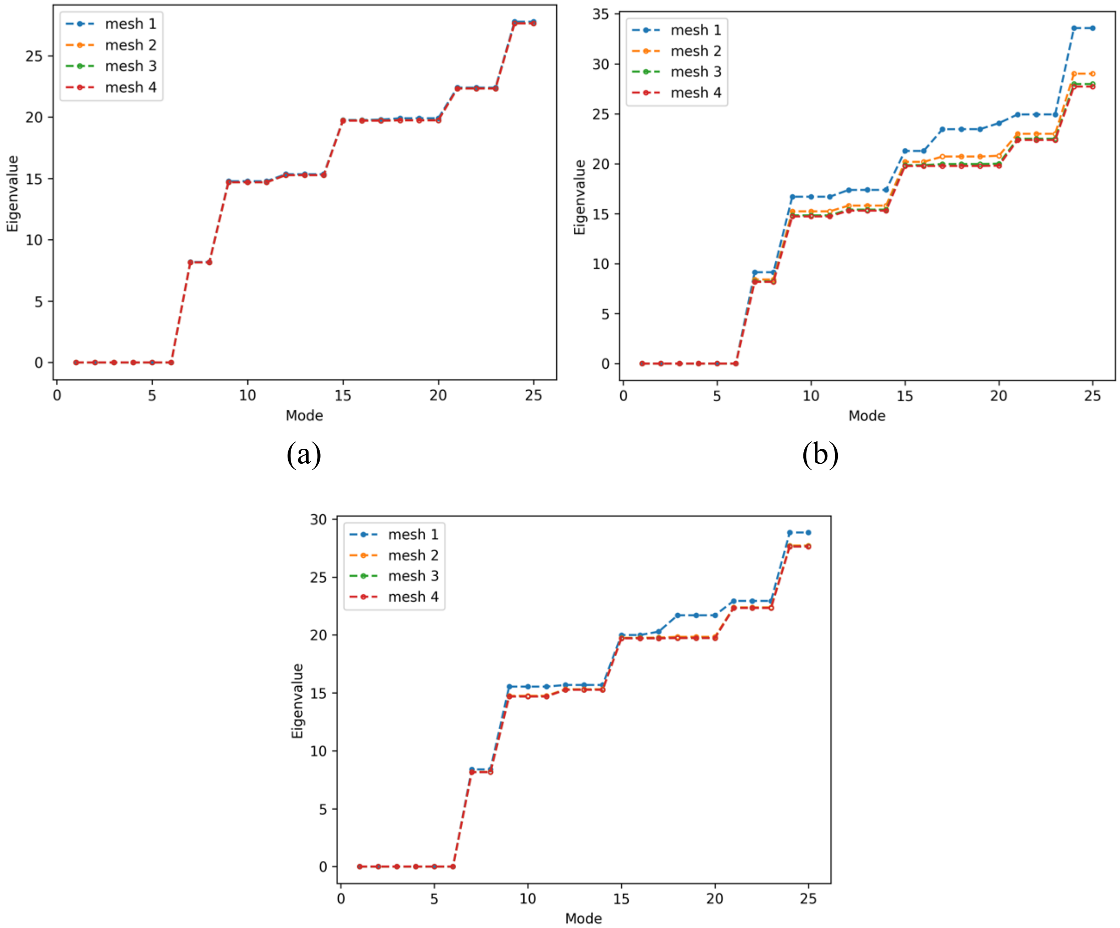
Not every block-structured FE mesh can be used directly as a precursor for generating a NURBS mesh suitable for analysis. Issues often arise when handling complex-geometry objects, and thus the meshes need to be inspected prior to conversion. The most common problem encountered is illustrated in the following example coming from a nuclear reactor pressure vessel solid mechanics model (see later sections) where the block-structured precursor mesh was generated using Pointwise. Figure 1a shows a non-conforming block-structured mesh, where three blocks are connected to one of the nodes of the orange block. Without any modifications of the block structure, the resulting NURBS mesh will have a mismatch in the continuity at the connection point and thus will not be analysis suitable. Splitting the orange block into two, as shown in Figure 1b, restores the continuity in the parameterization and renders the resulting NURBS mesh analysis suitable.

2.2 *Benchmarking and Assessment of Performance*

We consider two test cases: a unit cube and a shell structure modeled as a solid object. The latter geometry was provided by Dassault Systemes Simulia in the STEP file format. In each test case, we carry out a linear structural vibrations analysis and examine the convergence of the natural frequencies under mesh refinement. Accurate representation of the structural vibration modes is an indicator of the overall accuracy of a numerical method in structural mechanics. In the context of FSI, coupling with complex unsteady flows may trigger a structural response that activates the entire spectrum of the structural vibration modes. As a result, the structural discretization method that is accurate and robust across the entire spectrum, and not just in the low modes, will likely produce a more accurate FSI response. We perform a comparison between C^0-continuous linear and quadratic hexahedral FE and C^1-continuous quadratic NURBS (C^1-continuity holds only at the patch level). We note that generating quadratic FE meshes is a simple task for our meshing tools in that we only need to increase the knot multiplicity to two in each parametric direction, while leaving the remaining parts of the meshing framework unchanged.

2.2.1 *Unit Cube*

The unit cube has the simplest 3D geometry. We set the elastic-material Lamé parameters and density to unity. Figures 2a-c show the frequency spectra for all three discretizations, with four levels of mesh refinement in each discretization, focusing on the lower end of the spectrum. The eigenfrequency range was chosen to show where linear and quadratic FE discretizations begin deviating from the converged solution. The meshes are designed in such a way that, at each refinement level, all discretizations have comparable number of degrees of freedom (NDOFs). The eigenvalues computed match the values reported in the literature. For the NURBS discretization, the results for all four meshes are indistinguishable. The linear FE discretization shows clear separation between the curves. However, as expected, convergence occurs from the high side and the results for the third and fourth meshes are almost the same. The quadratic FE discretization shows errors on the first mesh, with essentially converged results for the subsequent three meshes.



(a)

(b)

(c)

Figure 2. Unit cube. Frequency spectra for four mesh refinements. (a) C^1-continuous quadratic NURBS; (b) C^0-continuous linear FE; (c) C^0-continuous quadratic FE.

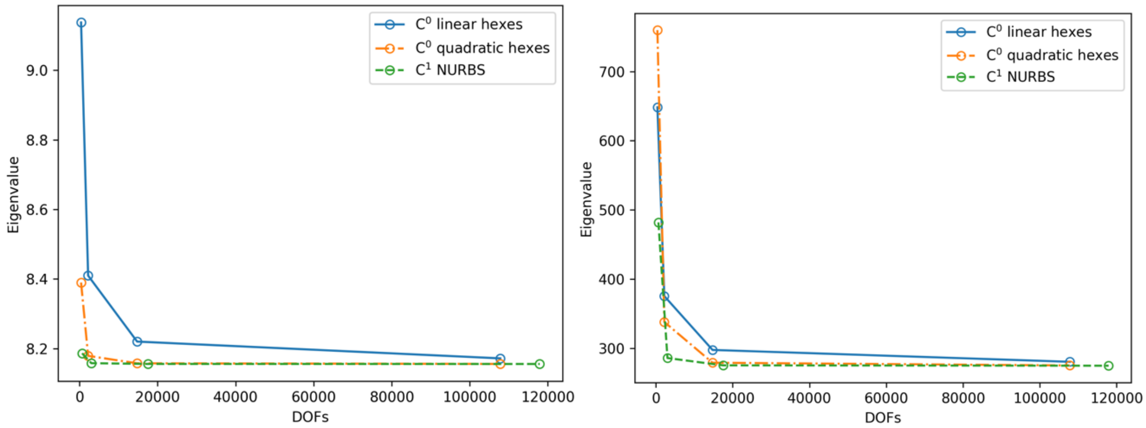
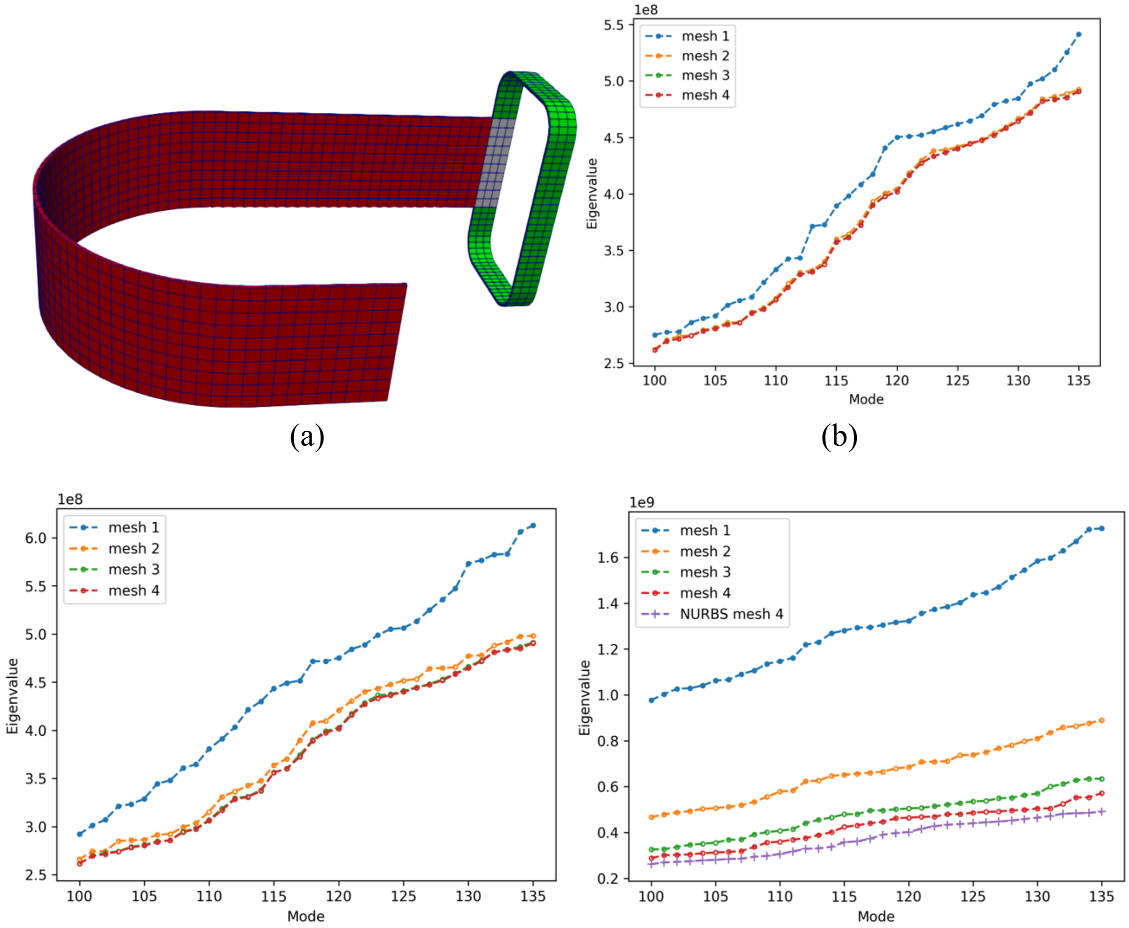


Figure 3. Unit cube. Mesh-refinement convergence. Left: Mode 8; Right: Mode 300.

Figure 3 shows the mesh refinement convergence for modes 8 and 300, representative of the low and high ends of the spectrum. For the low mode, both higher-order discretizations appear to be significantly more accurate than the linear FE discretization, which is expected and confirms the findings in the literature. For the high mode, at the coarsest refinement level, the error with the quadratic FE discretization is not only higher than the error with the NURBS discretization, but also higher than the error with the linear FE discretization. This clearly illustrates the inaccuracy and fragility of higher-order FE discretizations in high modes. Further mesh refinements, however, show faster convergence for both higher-order discretizations, also as expected. This example illustrates, in a 3D setting, that unlike the lower- and higher-order FE discretizations, the IGA discretization is accurate and robust across the entire frequency spectrum. This robustness is the likely explanation of the success of the IGA in nonlinear mechanics applications.

2.2.2 *Thin Shell Structure*



(a) (b)

(c) (d)

Figure 4. Thin shell structure. Mesh-refinement convergence. (a) Geometric model; (b) C^1-continuous quadratic NURBS; (c) C^0-continuous quadratic FE; (d) C^0-continuous linear FE.

Figure 4a shows the block-structured mesh. Material properties representative of steel are employed in the calculations. Overall length of the structure is 0.92 m, while its thickness is 6 mm. For each type of discretization, we have four mesh refinement levels, with the refinement taking place only in the in-plane directions. With the quadratic FE and NURBS, one element is used in the through-thickness direction, while with the linear FE, two linear elements, resulting in three nodes through the thickness in all discretization types. Figures 4b-c show the eigenvalues computed with the C^1-continuous quadratic NURBS and C^0-continuous quadratic FE. We focus on the spectrum range from mode 100 to mode 135. The eigenfrequency range chosen highlights a typical convergence behavior for this structure for the three discretization methods employed. With the quadratic FE, the solution essentially converges at the third mesh refinement level, while with the quadratic NURBS, already at the second level. Figure 4d shows the results for the linear FE. The errors are higher than what we saw for the unit cube, with convergence not achieved even at the fourth mesh refinement level. It is clear that, in thin-shell analysis, higher-order discretizations are far more effective than lower-order discretizations. It can also be seen that IGA brings increased accuracy to higher-order discretizations.

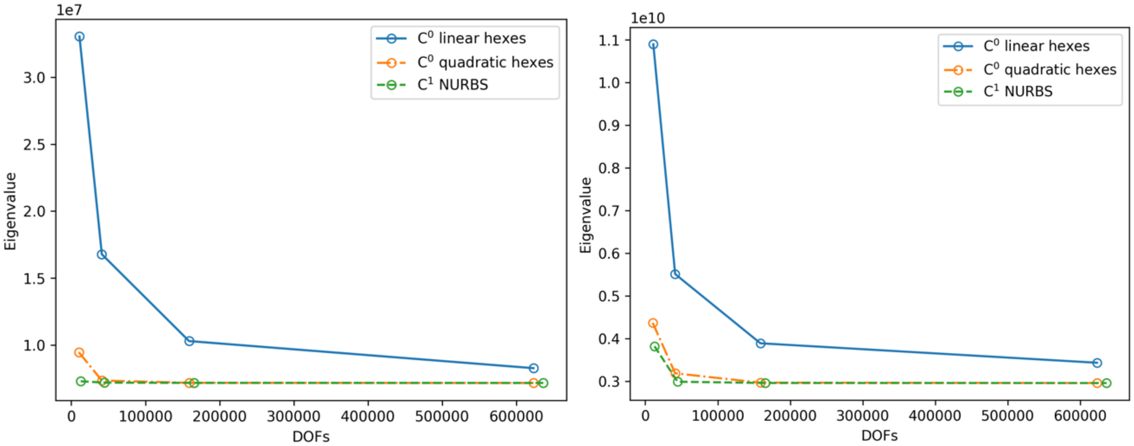


Figure 5. Thin shell structure. Mesh-refinement convergence. Left: Mode 30; Right: Mode 300.

Figure 5 shows the mesh refinement convergence for modes 30 and 300, representative of the low and high ends of the spectrum. The accuracy gap between the linear and higher-order discretizations is clearly visible in the figures. We note that in the low mode, the IGA is remarkably accurate even on the coarsest mesh. We also note that the coarsest-mesh quadratic FE is well behaving in the high mode.

2.3 *Demonstration on Some Challenging Applications*

2.3.1 *Structural Vibrations Analysis of a Nuclear Reactor Pressure Vessel*

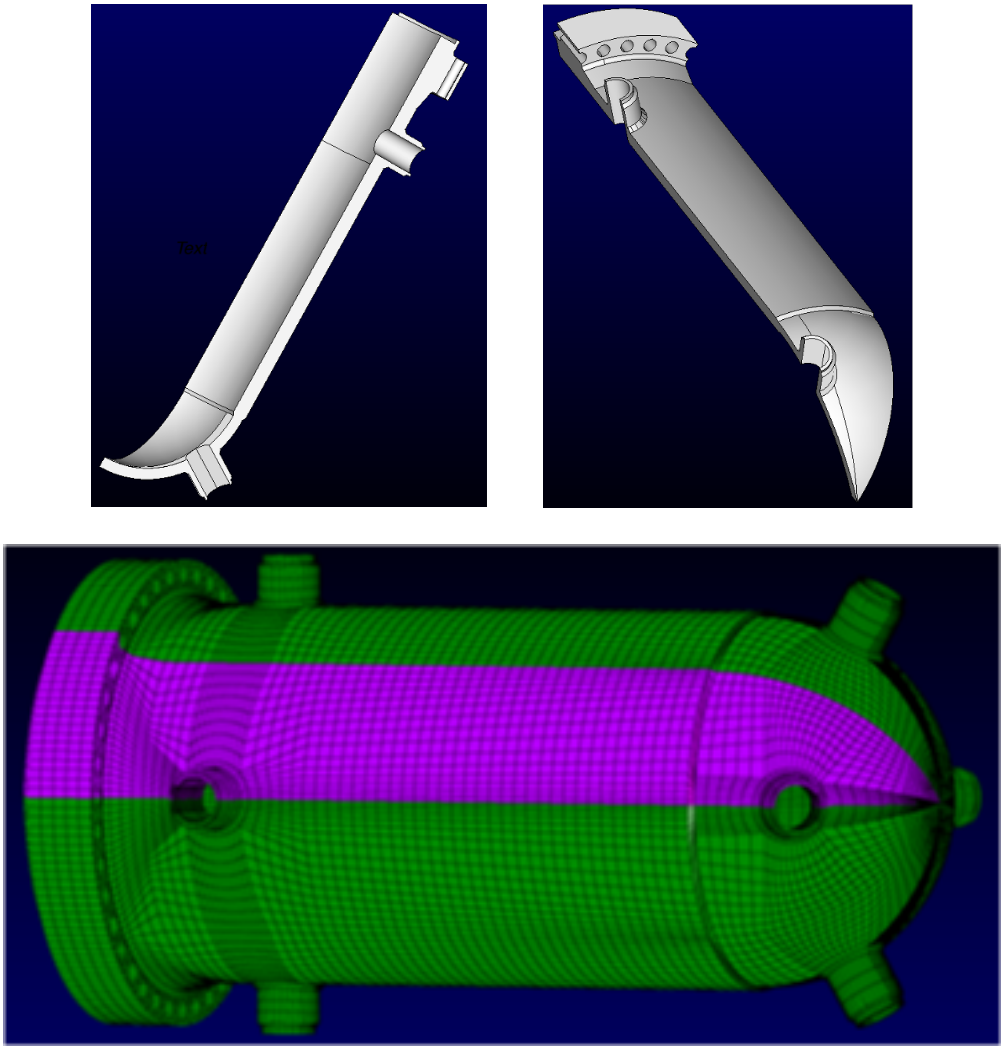


Figure 6. Nuclear reactor pressure vessel. Top: CAD model showing geometric features that pose challenges to meshing. Bottom: NURBS mesh generated and used in structural vibrations analysis.

The geometric model, corresponding to a nuclear reactor pressure vessel and shown in Figure 6, was provided by our industrial partner Dassault Systemes Simulia Inc. The meshing was carried out in Pointwise using the geometry from a CAD file (in *.stp format) provided by the industrial partner. Pointwise interprets the imported geometry and represents it using special entities called *quilts*. The nuclear-vessel geometry is represented using 75 quilts. Pointwise can automatically generate a quilt-based representation of the original geometry, however, in this example, a significant part of that representation required manual improvements to create surfaces and volumes that are suited for NURBS meshing. The NURBS mesh of a complete pressure vessel is shown in Figure 6. The vessel geometry has both shell- and solid-like features, which is not uncommon in practice.

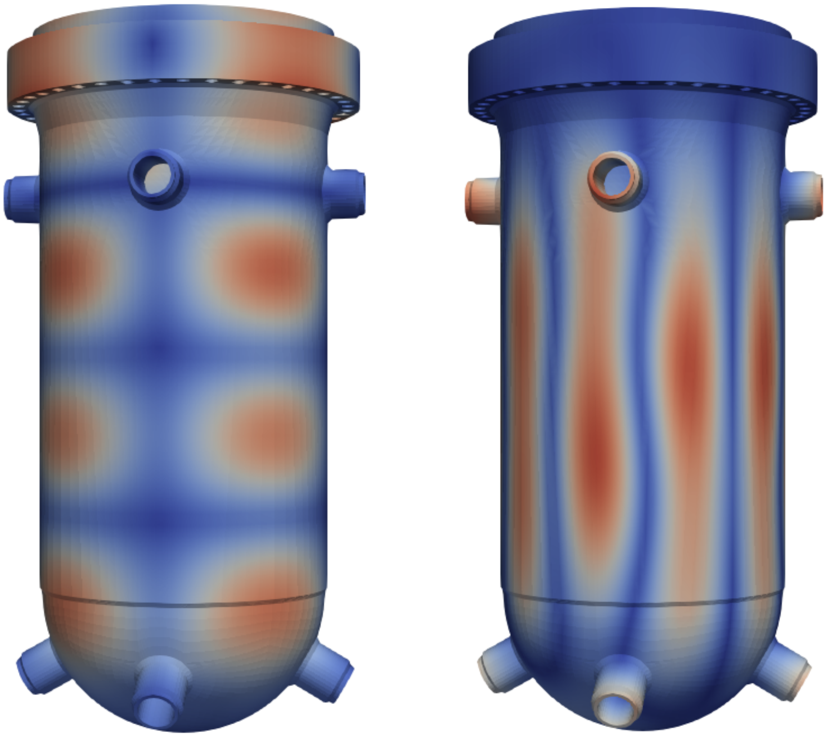
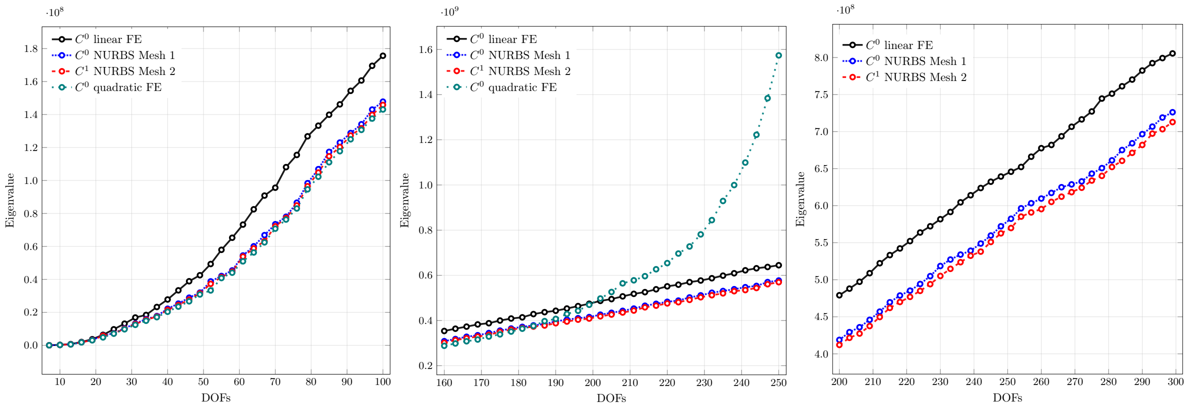


Figure 7. Nuclear reactor pressure vessel. Scaled displacement modes. Mode 35 (left) and mode 60 (right). The red and blue regions correspond to higher and lower values.

To carry out structural vibrations computations, we use the same material parameters as those for the thin shell structure. The total length of the vessel is 7.24 m, the maximum diameter (i.e., diameter at the flange) is 3.91 m, and the maximum thickness is 0.56 m. Figure 7 shows modes 35 and 60, computed the full geometry with a NURBS mesh. The modes look physically reasonable and are quite smooth, which is a key attribute of the IGA.



(a) (b) (c)

Figure 8. Nuclear reactor pressure vessel. Frequency spectra. (a) Low modes; (b) Medium modes; (c) High modes. Here “DOFs” denotes mode number.

In comparing the results from different meshes, only 1/8 of the vessel geometry is used. We note that it is rare to perform mesh refinement studies for such cases due to the geometric complexity. We use four different meshes: C^0-continuous linear FE (NDOF ~ 160K), C^0-continuous quadratic FE (NDOF ~ 160K), and C^1-continuous quadratic NURBS mesh 1 (NDOF ~ 45K) and mesh 2 (NDOF ~ 220K). Figures 8a-c show the frequency spectra for the low, medium, and high modes. We see in Figure 8a that, as the mode number increases, the linear FE discretization clearly loses accuracy compared to the higher-order discretizations, which are very close to each other. In Figure 8b, we see that at around mode 200, quadratic FE rapidly and severely loses accuracy compared to linear FE and quadratic NURBS. As the mode number increases further in Figure 8c, the gap between linear FE and quadratic NURBS widens. We also start seeing some difference between the NURBS mesh 1 and mesh 2, suggesting that capturing even higher modes will require another level of mesh refinement. The results for the nuclear reactor pressure vessel clearly illustrate yet again the power of the IGA, where even at the coarse discretization level the spectrum is very well approximated, both in the low- and high-mode regimes.

2.3.3 *Flow Simulation with Moving Meshes and Contact*

The NURBS meshing software was extensively used in very challenging computations with moving meshes and contact. The computation was for car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. These computations with both actual-contact and high-resolution boundary-layer representations were the first ever of its kind. Figure 9 shows the car and tire models. Figure 10 shows the global mesh around the car body and tires. Figure 11 shows the local domains used in the multiscale-computation framework. Local domains are for the front tire, wake of the front tire, and rear tire. Figure 12 shows the local meshes used in the multiscale-computation framework. Figure 13 shows the details of the local mesh around a tire. Figure 14 shows the flow patterns around the car and tires, from the global computation of the multiscale-computation framework. Figure 15 shows the flow patterns around the tires, from the local computations of the multiscale-computation framework.

Figure 9. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Car body and tire models.

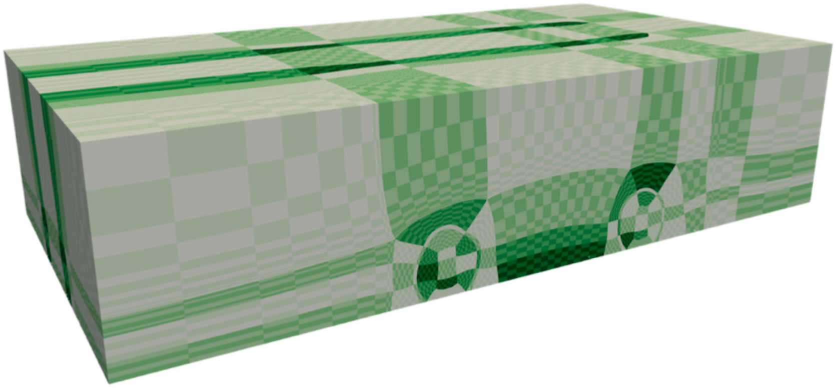


Figure 10. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Global mesh around the car body and tires.

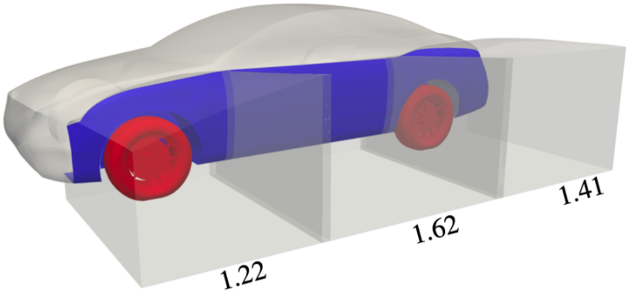


Figure 11. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Local domains used in the multiscale-computation framework. Local domains for the front tire, wake of the front tire, and rear tire.

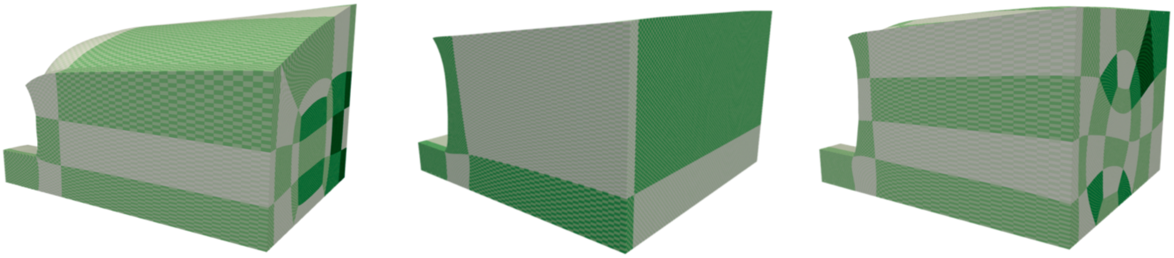


Figure 12. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Local meshes used in the multiscale-computation framework.

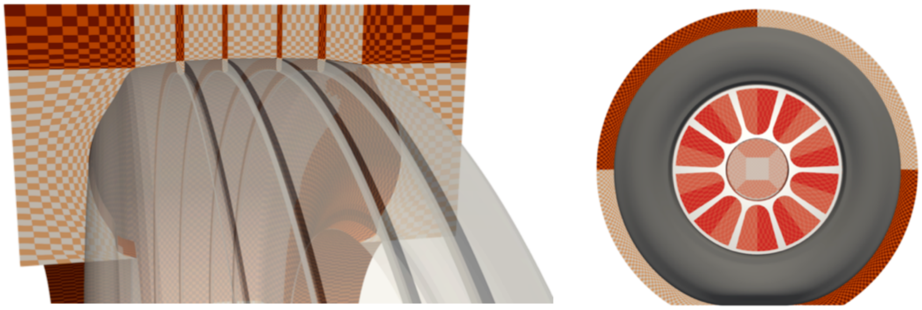


Figure 13. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Details of the local mesh around a tire.

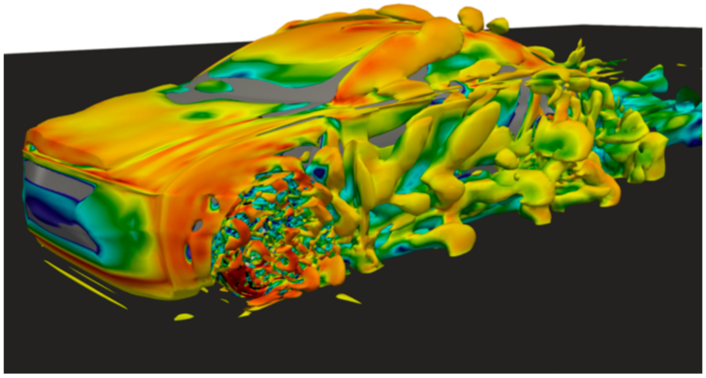


Figure 14. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Flow patterns around the car and tires, from the global computation of the multiscale-computation framework.

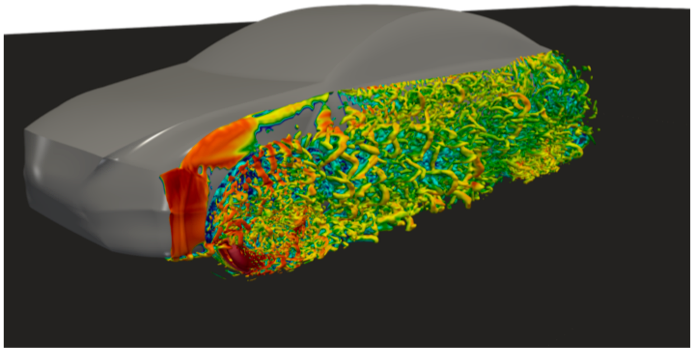


Figure 15. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. Flow patterns around the tires, from the local computations of the multiscale-computation framework.

3. Dissemination, Marketing and Commercialization

Significant effort in this STTR project was devoted to the dissemination and marketing of the results to industry, lab and academic collaborators/partners. This activity presents the first steps toward commercialization of the technology developed in this project.

3.1 *NURBS Meshing Tutorial*

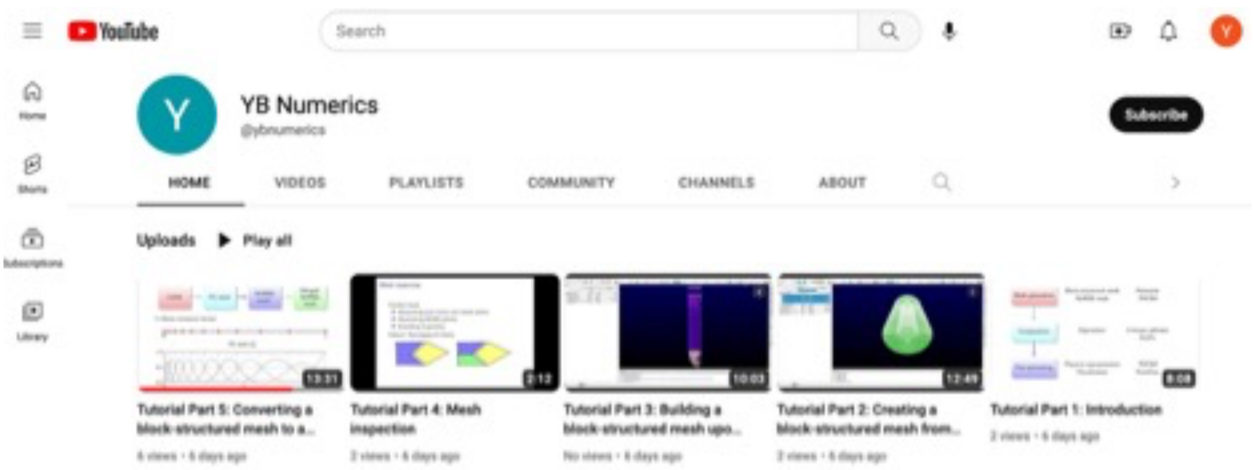


Figure 16. Snapshot of the YouTube channel containing the NURBS meshing tutorial videos.

We developed a five-part video tutorial with high quality video and sound explaining the NURBS mesh generation process. The goal of the video tutorial is to clearly show the steps of the process to generate IGA meshes using the methods, algorithms, codes, and tools developed and used in this STTR project. The material in the tutorial is presented in a manner that will enable the users to follow the steps and create their own geometry models and IGA meshes for a variety of analyses. The videos cover the following topics:

- Creating a block-structured mesh “from scratch” or from a CAD file in Pointwise.
- Generating NURBS meshes in the Bezier extraction format.
- Post-processing and visualization of the IGA computational results.
- Discussion of the relative per degree of freedom accuracy of NURBS solution relative to their FEM counterparts.

The five tutorials recorded were used to create a YouTube channel (see Figure 16) and may be found at the following link:

https://www.youtube.com/channel/UCs2af5adG3LnIpX_g8WSidQ

To facilitate technology transition, we began sharing the link with the project partners.

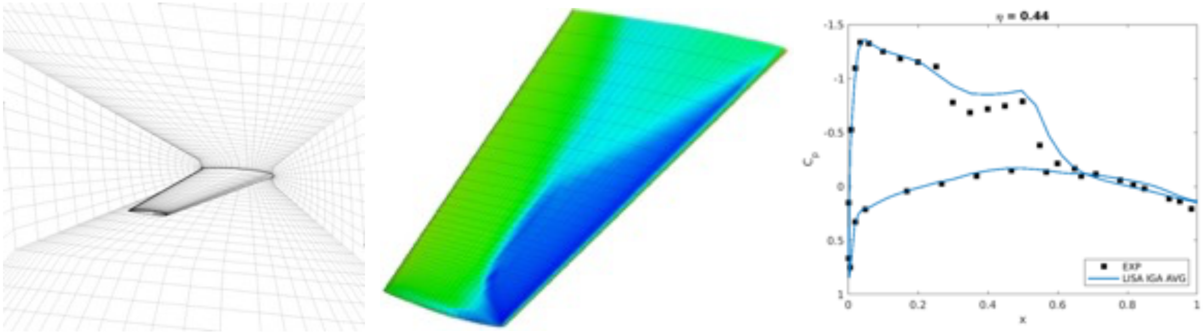
3.2 *Engaging Industry, Research Labs and Academia*

Our technical abstract was accepted for presentation at IGA 2022 that took place in Banff, Canada on November 6-9, 2022. This is an annual conference on Isogeometric Analysis (IGA) and is a premier annual event in the IGA community. The YB Numerics (YBN) team delivered a technical presentation on the work and results generated as part of this STTR project.

We wrote a book chapter detailing the work on NURBS meshing and structural vibrations results obtained in this project. The book chapter was submitted for review. It was reviewed favorably, we revised it, and received final acceptance for publication in the Springer book series titled "Frontiers in Computational Fluid-Structure Interaction and Flow Simulation". We are now finalizing an expanded and improved version of this material to be published as an archival journal article.

To introduce industry and labs to our meshing methods and tools, the YBN team visited Dassault Systemes Simulia Inc. in Johnston, RI, hosted by its Chief Scientific Officer for Structures, Dr. V. Oancea. The YBN team made a presentation to several teams working on ABAQUS Software development on the recent advances in IGA, devoting a significant portion of the presentation to showcasing the NURBS meshing techniques developed in this project and the superior performance of IGA for structural vibrations.

YBN and the Rice University-Waseda University (RUWU) teams met with researchers from the ARL Vehicles Technology Directorate (ARL-VTD) to discuss the application of NURBS meshing methods to hypersonic applications. The YBN team made a presentation to the ARL-VTD researchers on the meshing tools in support of IGA simulations. The teams are now in conversation about combining IGA meshing and efforts in hypersonic modeling to study morphing objects in hypersonic flight.



(a) (b) (c)

Figure 17. Flow over ONERA M6 wing. (a) NURBS mesh; (b) Time-averaged pressure distribution on the wing surface; (c) Time-averaged pressure coefficient on an axial cut along the wing: Comparison with the experimentally measured data is provided.

The RUWU and YBN teams started a “test user” collaboration with the Computational Fluid and Structural Mechanics group at the University of Calgary. The U Calgary group, with guidance from the RUWU and YBN teams, are now using the NURBS mesh generation tools that are being developed in the STTR project. This will be a case of practical use of the mesh generation tools by those outside the RUWU and YBN teams. Lessons learned from this collaboration will help us improve the wider usability of the tools. The collaboration with the U Calgary group of Prof. A. Korobenko is on the simulation of compressible flows. We focused on a problem of 3D compressible transonic flow over the ONERA M6 wing. NURBS meshing in this case made use of an external CAD file that defined the wing surfaces and the bounding domain. A snapshot of the 3D quadratic NURBS mesh of the ONERA M6 wing is shown in Figure 17a. A preliminary compressible-flow computation was carried out for this case on a fairly coarse mesh. The flow solution (see Mach number contours in Figure 17b) appears stable and consistent with the results presented in the open literature for this case. A double shock feature on the wing top surface is captured well despite the relatively coarse nature of the mesh. Experimental comparison, shown in Figure 17c, shows that the pressure profile is captured quite well. Some deviation from the experimental data is observed, likely due to the relatively coarse NURBS mesh employed in the simulation compared to what is typically used to simulate this case using traditional methods.

The NURBS meshing software is being used at Takizawa Lab at Waseda University (Japan) in an applied research project in collaboration with ISUZU Motors. The project is focusing on flow analysis in an exhaust pipe, including the diesel oxidation catalyst (DOC) and diesel particulate filter. Estimating the clogging of the DOC cell openings caused by soot piling is one of the practical objectives of the project. This is a good example of how the NURBS meshing software is directly contributing to a real-world simulation that is important to industry.