ROUTING AND ACTION

MEMORANDUM

ROUTING

TO:(1) Network, Cyber, and Computational Sciences Branch (NC&CS) (Balu, Radhakrishnan)

Report is available for review

(2) Proposal Files   Report No.:   Proposal Number: 67786-NC.1

DESCRIPTION OF MATERIAL

CONTRACT OR GRANT NUMBER: W911NF-17-1-0046

INSTITUTION: William Marsh Rice University

PRINCIPAL INVESTIGATOR: Tayfun Tezduyar

TYPE REPORT: Final Report

DATE RECEIVED: 8/17/23 5:46PM

PERIOD COVERED: 1/3/17 12:00AM through 3/2/23 12:00AM

TITLE: Final Report: Multiscale Space-Time Methods for Fluid-Structure Interaction Analysis with Topology Change, Slip Interfaces and Thermal Effects

ACTION TAKEN BY DIVISION

(x) Report has been reviewed for technical sufficiency and IS [ ] IS NOT [x] satisfactory.

( ) Based on my technical review, I have identified no OPSEC or Technology Protection concerns that need to be addressed regarding this report.

(x) Perfomance of the research effort was accomplished in a satisfactory manner and all other technical requirements have been fulfilled.

(x) Based upon my knowledge of the research project, I agree with the patent information disclosed.

Approved by SSL\RADHAKRISHNAN.BALU on 9/26/23 2:57PM

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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			Tayfun Tezduyar
UU	UU	UU	UU		19b. TELEPHONE NUMBER 713-348-6051

RPPR Final Report
as of 26-Sep-2023

Agency Code: 21XD

Proposal Number: 67786NC | **Agreement Number: W911NF-17-1-0046**

INVESTIGATOR(S):

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Final Report for Period Beginning 03-Jan-2017 and Ending 02-Mar-2023
Title: Multiscale Space-Time Methods for Fluid-Structure Interaction Analysis with Topology Change, Slip Interfaces and Thermal Effects
Begin Performance Period: 03-Jan-2017 | **End Performance Period:** 02-Mar-2023
Report Term: 0-Other

Submitted By: Tayfun Tezduyar | Email: tezduyar@rice.edu
Phone: (713) 348-6051

Distribution Statement:

STEM Degrees: 10 **STEM Participants:** 3

Major Goals: The major goal of this project was to develop a new set of integrated multiscale space-time (ST) methods for fluid-structure interaction (FSI) analysis involving the fundamental challenges of topology change in the domain, slip interfaces between the subdomains, and multiscale coupling between the flow and thermal transport. The ST Variational Multiscale (ST-VMS) method we developed earlier was giving us, in addition to a VMS turbulence model, the “ST accuracy.” Like an arbitrary Lagrangian-Eulerian (ALE) method, the ST-VMS moves with the fluid-solid interfaces the high-resolution meshes placed there. With a new ST-VMS method we targeted developing in this project, we maintain those high-resolution meshes even when there is a topology change in the domain, such as contact between solid surfaces. We also proposed in this project developing the ST-VMS version of the variationally consistent slip interface methods that have recently been successful in the ALE-VMS context. With that, we can handle the subdomains that contain spinning structures with the “ST accuracy.” With a new ST-VMS method we also proposed developing for coupled flow and thermal-transport equations, we can have a method that is multiscale in the way small-scale thermo-fluid behavior is represented in the computations. These new methods, when properly integrated together, enable successfully addressing the formidable computational challenges of a wide range of FSI applications.

Accomplishments: In computation of flow problems with moving solid surfaces, moving-mesh methods such as the Space-Time (ST) Variational Multiscale method enable mesh-resolution control near the solid surfaces and thus high-resolution boundary-layer representation. There was, however, a perception that in computations where the solid surfaces come into contact, high-resolution boundary-layer representation and actual-contact representation without leaving a mesh protection opening between the solid surfaces were mutually exclusive objectives in a practical sense. Further development and enhancement of the ST Topology Change (ST-TC) method in this project very much changed the perception. The two objectives are no longer mutually exclusive. The ST-TC makes moving-mesh computation possible even without leaving a mesh protection opening. The contact is represented as an actual contact and the boundary layer is represented with high resolution. Elements collapse or are reborn as needed, and that is attainable in the ST framework while retaining the computational efficiency at a practical level. The ST-TC now has strong record of achieving the two objectives that were long seen as mutually exclusive. With the ST-TC and other ST computational methods introduced before and after, it has been possible to address many of the challenges encountered in conducting flow analysis with boundary layer and contact representation, in the presence of additional intricacies such as geometric complexity, isogeometric discretization, and rotation or deformation of the solid surfaces. The flow analyses conducted with these ST methods include car and tire aerodynamics with road contact and tire deformation, a first-ever computation. Our research efforts in this project resulted in a large number of publications acknowledging this grant: 43 journal articles indexed by the Web of Science, 5 other journal articles, 11 book chapters, and 1 conference paper.

Training Opportunities: Nothing to report.

Results Dissemination: The results dissemination has mostly been in the form of publications acknowledging this grant: 43 journal articles indexed by the Web of Science, 5 other journal articles, 11 book chapters, and 1 conference paper. The dissemination has also been in the form of invited lectures at conferences and to student groups and at seminars. The PI gave 3 plenary lectures, 1 semi-plenary lecture, 2 keynote lectures, and 35 other invited lectures.

Honors and Awards: The PI received the following honors and awards during the grant period:

2107 Web of Science Highly Cited Researcher (Engineering) (Computer Science)

2018 Ted Belytschko Applied Mechanics Award, American Society of Mechanical Engineers

2018 Web of Science Highly Cited Researcher (Cross-Field)

2019 Computational Mechanics Award, Asian Pacific Association for Computational Mechanics

2021 Honorary Member, Japan Association for Computational Mechanics

Protocol Activity Status:

Technology Transfer: The PI visited the ARL, as arranged by Dr. Joe Myers. This was followed by an offer of mesh generation scripts to ARL.

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Reha Avsar
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Dino Barrios
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Takashi Kuraishi
Person Months Worked: 10.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Eli Case
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:

National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: **Publication Status:** 1-Published
Journal: Mathematical Models and Methods in Applied Sciences
Publication Identifier Type: DOI Publication Identifier: 10.1142/s0218202523500380
Volume: 33 Issue: 08 First Page #:
Date Submitted: Date Published: 5/15/23 12:00AM
Publication Location:
Article Title: Variational multiscale method stabilization parameter calculated from the strain-rate tensor
Authors: Kenji Takizawa, Yuto Otoguro, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Publication Type: Journal Article Peer Reviewed: **Publication Status:** 1-Published
Journal: Computational Mechanics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s00466-019-01669-4
Volume: 64 Issue: 1 First Page #:
Date Submitted: Date Published: 2/19/19 12:00AM
Publication Location:
Article Title: Medical-image-based aorta modeling with zero-stress-state estimation
Authors: Takafumi Sasaki, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Publication Type: Journal Article Peer Reviewed: **Publication Status:** 1-Published
Journal: Computational Mechanics
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Date Submitted: Date Published: 3/11/20 12:00AM
Publication Location:
Article Title: A low-distortion mesh moving method based on fiber-reinforced hyperelasticity and optimized zero-stress state
Authors: Kenji Takizawa, Tayfun E. Tezduyar, Reha Avsar,
Keywords: Applied Mathematics
Abstract:
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Publication Identifier Type: DOI Publication Identifier: 10.1142/s0218202522500579
Volume: 32 Issue: 12 First Page #:
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Publication Location:
Article Title: Flow computation with the Space–Time Isogeometric Analysis and higher-order basis functions in time
Authors: Yang Liu, Kenji Takizawa, Yuto Otoguro, Takashi Kuraishi, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Publication Type: Journal Article Peer Reviewed: **Publication Status:** 1-Published
Journal: Computational Mechanics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s00466-019-01809-w
Volume: 65 Issue: 4 First Page #:
Date Submitted: Date Published: 1/3/20 12:00AM
Publication Location:
Article Title: Element length calculation in B-spline meshes for complex geometries
Authors: Yuto Otoguro, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Journal: Computers & Fluids
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.compfluid.2018.05.019
Volume: 179 Issue: First Page #:
Date Submitted: Date Published: 1/1/19 12:00AM
Publication Location:
Article Title: Turbocharger turbine and exhaust manifold flow computation with the Space–Time Variational Multiscale Method and Isogeometric Analysis
Authors: Yuto Otoguro, Kenji Takizawa, Tayfun E. Tezduyar, Kenichiro Nagaoka, Sen Mei,
Keywords: General Engineering
Abstract:
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Publication Identifier Type: DOI Publication Identifier: 10.1007/s00466-020-01965-4
Volume: 67 Issue: 3 First Page #:
Date Submitted: Date Published: 2/13/21 12:00AM
Publication Location:
Article Title: U-duct turbulent-flow computation with the ST-VMS method and isogeometric discretization
Authors: Levent Aydinbakar, Kenji Takizawa, Tayfun E. Tezduyar, Daisaku Matsuda,
Keywords: Applied Mathematics
Abstract:
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Publication Identifier Type: DOI Publication Identifier: 10.1007/s00466-018-1595-4
Volume: 63 Issue: 2 First Page #:
Date Submitted: Date Published: 7/2/18 12:00AM
Publication Location:
Article Title: Compressible-flow geometric-porosity modeling and spacecraft parachute computation with isogeometric discretization
Authors: Taro Kanai, Kenji Takizawa, Tayfun E. Tezduyar, Tatsuya Tanaka, Aaron Hartmann,
Keywords: Applied Mathematics
Abstract:
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Journal: Computational Mechanics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s00466-018-1642-1
Volume: 63 Issue: 6 First Page #:
Date Submitted: Date Published: 10/13/18 12:00AM
Publication Location:
Article Title: Tire aerodynamics with actual tire geometry, road contact and tire deformation
Authors: Takashi Kuraishi, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
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Publication Location:
Article Title: Boundary layer mesh resolution in flow computation with the Space–Time Variational Multiscale method and isogeometric discretization
Authors: Takashi Kuraishi, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Publication Type: Journal Article Peer Reviewed: **Publication Status:** 1-Published
Journal: Computational Mechanics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s00466-020-01910-5
Volume: 66 Issue: 6 First Page #:
Date Submitted: Date Published: 8/31/20 12:00AM
Publication Location:
Article Title: Space–Time Variational Multiscale Isogeometric Analysis of a tsunami-shelter vertical-axis wind turbine
Authors: Yuto Otoguro, Hiroki Mochizuki, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Date Submitted: Date Published: 2/20/20 12:00AM
Publication Location:
Article Title: Ventricle-valve-aorta flow analysis with the Space–Time Isogeometric Discretization and Topology Change
Authors: Takuya Terahara, Kenji Takizawa, Tayfun E. Tezduyar, Atsushi Tsushima, Kensuke Shiozaki,
Keywords: Applied Mathematics
Abstract:
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Volume: 71 Issue: 1 First Page #:
Date Submitted: Date Published: 10/6/22 12:00AM
Publication Location:
Article Title: Carrier-Domain Method for high-resolution computation of time-periodic long-wake flows
Authors: Yang Liu, Kenji Takizawa, Tayfun E. Tezduyar, Takashi Kuraishi, Yufei Zhang,
Keywords: Applied Mathematics
Abstract:
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Volume: 65 Issue: 4 First Page #:
Date Submitted: Date Published: 1/10/20 12:00AM
Publication Location:
Article Title: Heart valve isogeometric sequentially-coupled FSI analysis with the space–time topology change method
Authors: Takuya Terahara, Kenji Takizawa, Tayfun E. Tezduyar, Yuri Bazilevs, Ming-Chen Hsu,
Keywords: Applied Mathematics
Abstract:
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Date Submitted: Date Published: 4/23/22 12:00AM
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Article Title: A hyperelastic extended Kirchhoff–Love shell model with out-of-plane normal stress: I. Out-of-plane deformation
Authors: Yasutoshi Taniguchi, Kenji Takizawa, Yuto Otoguro, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Article Title: Aorta zero-stress state modeling with T-spline discretization
Authors: Takafumi Sasaki, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Journal: Computers & Fluids
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.compfluid.2017.04.017
Volume: 158 Issue: First Page #:
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Publication Location:
Article Title: Space–time VMS computational flow analysis with isogeometric discretization and a general-purpose NURBS mesh generation method
Authors: Yuto Otoguro, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: General Engineering
Abstract:
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Journal: Computational Mechanics
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Volume: 64 Issue: 5 First Page #:
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Article Title: Space–time VMS flow analysis of a turbocharger turbine with isogeometric discretization: computations with time-dependent and steady-inflow representations of the intake/exhaust cycle
Authors: Yuto Otoguro, Kenji Takizawa, Tayfun E. Tezduyar, Kenichiro Nagaoka, Reha Avsar, Yutong Zhang,
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Article Title: Space–time VMS isogeometric analysis of the Taylor–Couette flow
Authors: Levent Aydinbakar, Kenji Takizawa, Tayfun E. Tezduyar, Takashi Kuraishi,
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Article Title: Space–time computational analysis of tire aerodynamics with actual geometry, road contact, tire deformation, road roughness and fluid film
Authors: Takashi Kuraishi, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Journal: Computers & Fluids
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.compfluid.2018.05.025
Volume: 179 Issue: First Page #:
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Article Title: Mesh refinement influence and cardiac-cycle flow periodicity in aorta flow analysis with isogeometric discretization
Authors: Kenji Takizawa, Tayfun E. Tezduyar, Hiroaki Uchikawa, Takuya Terahara, Takafumi Sasaki, Ayaka Yos
Keywords: General Engineering
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Article Title: Wind turbine wake computation with the ST-VMS method and isogeometric discretization: Directional preference in spatial refinement
Authors: Fulin Zhang, Takashi Kuraishi, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
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Volume: 63 Issue: 4 First Page #:
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Publication Location:
Article Title: Isogeometric hyperelastic shell analysis with out-of-plane deformation mapping
Authors: Kenji Takizawa, Tayfun E. Tezduyar, Takafumi Sasaki,
Keywords: Applied Mathematics
Abstract:
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Journal: Mathematical Models and Methods in Applied Sciences
Publication Identifier Type: DOI Publication Identifier: 10.1142/s0218202520500402
Volume: 30 Issue: 11 First Page #:
Date Submitted: Date Published: 10/1/20 12:00AM
Publication Location:
Article Title: Element-splitting-invariant local-length-scale calculation in B-Spline meshes for complex geometries
Authors: Yuki Ueda, Yuto Otoguro, Kenji Takizawa, Tayfun E. Tezduyar,
Keywords: Applied Mathematics
Abstract:
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Tayfun Tezduyar
Signature Date: 8/17/23 5:46PM

Abstract

In computation of flow problems with moving solid surfaces, moving-mesh methods such as the Space-Time (ST) Variational Multiscale method enable mesh-resolution control near the solid surfaces and thus high-resolution boundary-layer representation. There was, however, a perception that in computations where the solid surfaces come into contact, high-resolution boundary-layer representation and actual-contact representation without leaving a mesh protection opening between the solid surfaces were mutually exclusive objectives in a practical sense. Further development and enhancement of the ST Topology Change (ST-TC) method in this project very much changed the perception. The two objectives are no longer mutually exclusive. The ST-TC makes moving-mesh computation possible even without leaving a mesh protection opening. The contact is represented as an actual contact and the boundary layer is represented with high resolution. Elements collapse or are reborn as needed, and that is attainable in the ST framework while retaining the computational efficiency at a practical level. The ST-TC now has a strong record of achieving the two objectives that were long seen as mutually exclusive. With the ST-TC and other ST computational methods introduced before and after, it has been possible to address many of the challenges encountered in conducting flow analysis with boundary layer and contact representation, in the presence of additional intricacies such as geometric complexity, isogeometric discretization, and rotation or deformation of the solid surfaces. The methods integrated with the ST-TC are the ST-VMS, which serves as the core method, the ST Slip Interface (ST-SI) method, and ST isogeometric analysis (ST-IGA). The flow analyses conducted with these ST methods include car and tire aerodynamics with road contact and tire deformation, a first-ever computation.

Objectives

Year 1 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, and ST-IGA methods.

Year 2 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, and ST-IGA methods on problems with complex geometries.

Year 3 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, ST-TC, and ST-IGA methods on tire aerodynamics with road contact.

Year 4 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, ST-TC, and ST-IGA methods on car and tire aerodynamics with road contact.

Findings

Year 1 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, and ST-IGA methods

The ST-SI-IGA is the synthesis of the ST-VMS, ST-SI, and ST-IGA methods. The moving-mesh feature of the ST-VMS enables mesh resolution control and accurate representation of boundary layers near moving solid surfaces. Compared to semi-discrete methods, the ST context brings to flow solution higher accuracy in space and time. The ST-SI accurately connects the parts of the solution obtained over two mesh zones with nonmatching meshes at the SI between the zones, and thus we can still use the ST-VMS as a moving-mesh method. With that, we can compute flow problems with rotating solid surfaces. The ST-IGA brings superior accuracy in representing the problem geometry and flow solution. Figure 1 from [1] shows one of the earliest test computations with the ST-SI-IGA.

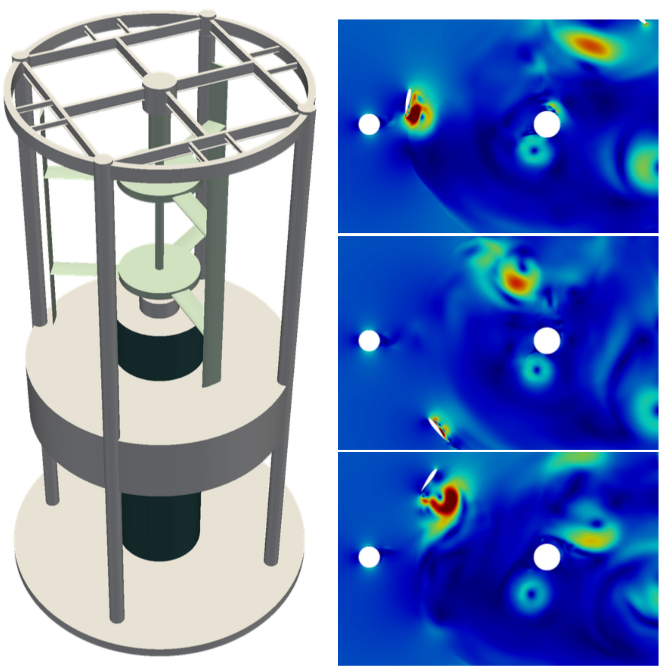

Figure 1. Aerodynamics of a vertical-axis wind turbine, computed in 2D with the ST-SI-IGA. Wind turbine model and the velocity magnitude at three instants. For the 3D computation, see [1].

Year 2 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, and ST-IGA methods on problems with complex geometries

While the IGA discretization offers superior accuracy, IGA mesh generation for problems with complex geometries is known to be a significant challenge. We have overcome that challenge with a NURBS mesh generation method we developed [2]. We have successfully extended the scope of the ST-SI-IGA to problems with moving solid surfaces and complex geometries. We can conduct high-fidelity computations with fewer control points (i.e. unknowns) compared to standard discretization methods such as the finite differences, finite volumes, and finite elements. Figure 2 from [2] shows the computation for a turbocharger turbine and exhaust manifold, carried out with the ST-SI-IGA.

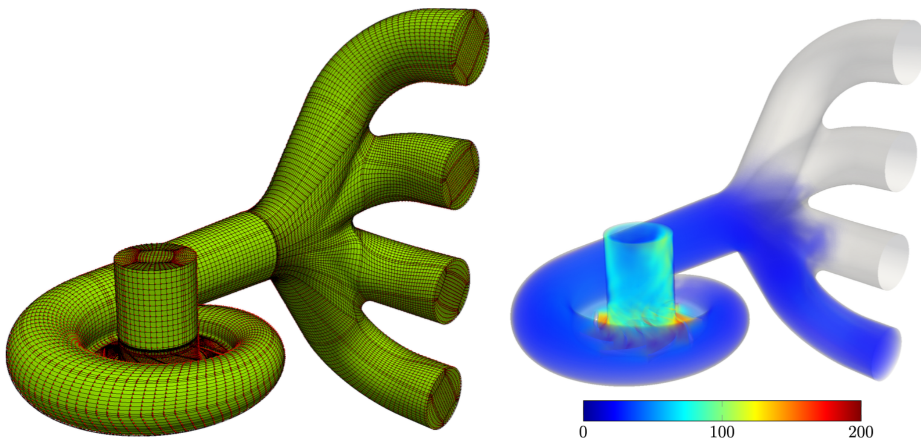

Figure 2. Flow in a turbocharger turbine and exhaust manifold, carried out with the ST-SI-IGA. NURBS mesh and the velocity magnitude (m/s) at an instant.

Year 3 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, ST-TC, and ST-IGA methods on tire aerodynamics with road contact

The ST-SI-TC-IGA is the synthesis of the ST-VMS, ST-SI, ST-TC, and ST-IGA methods. The ST-TC makes moving-mesh computation possible even without leaving a mesh protection opening. The contact is represented as an actual contact and the boundary layer is represented with high resolution. Elements collapse or are reborn as needed, and that is attainable in the ST framework while retaining the computational efficiency at a practical level. The ST-TC now has a strong record of achieving the two objectives that were long seen as mutually exclusive. It has been successfully applied to several classes of challenging problems with complex geometries. Figure 3 from [3] shows tire aerodynamics with near-actual tire geometry, road contact, and tire deformation, computed with the ST-SI-TC-IGA. This computation was first of its kind.

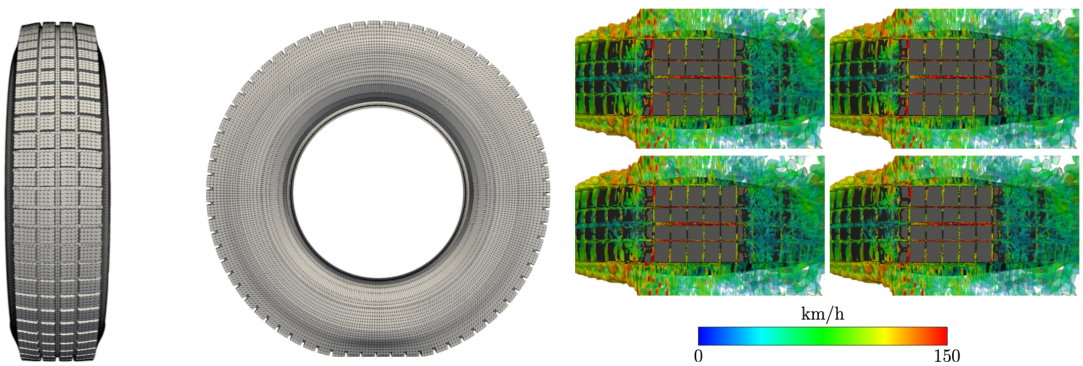

Figure 3. Tire aerodynamics with near-actual tire geometry, road contact, and tire deformation, computed with the ST-SI-TC-IGA. Tire model and isosurfaces corresponding to a positive value of the second invariant of the velocity gradient tensor, colored by the velocity magnitude, viewed from the bottom. The gray zones are the contact areas.

Year 4 Objective: Test-prove the synthesis of the ST-VMS, ST-SI, ST-TC, and ST-IGA methods on car and tire aerodynamics with road contact

Extending the ST-SI-TC-IGA to complex-geometry problems like the car and tire aerodynamics with road contact requires overcoming the IGA mesh generation challenge encountered in such never-before-attempted computations. We have overcome that challenge with a combination of the NURBS mesh generation methods developed in [2] and in [4]. Figure 4 from [4] shows car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation. This computation was first of its kind. While the method in [4] was developed in the context of car and tire aerodynamics, the underlying concepts are more general and are applicable to other classes of flow problems with complex geometries.

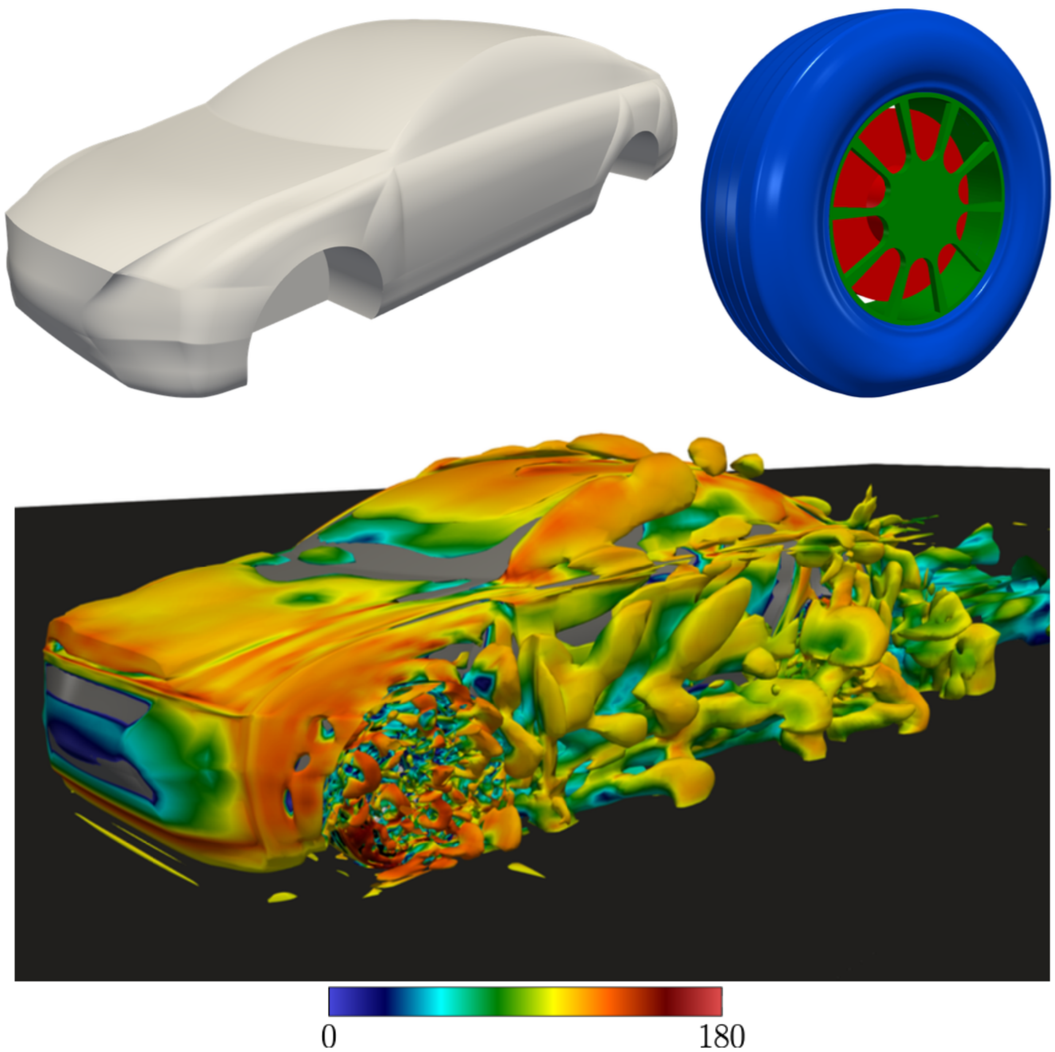

Figure 4. Car and tire aerodynamics with near-actual car and tire geometries, road contact, and tire deformation, computed with the ST-SI-TC-IGA. Car body and tire models and isosurfaces corresponding to a positive value of the second invariant of the velocity gradient tensor, colored by the velocity magnitude (km/h).

References

[1] Y. Otoguro, H. Mochizuki, K. Takizawa and T.E. Tezduyar, “Space-Time Variational Multiscale Isogeometric Analysis of a Tsunami-Shelter Vertical-Axis Wind Turbine”, *Computational Mechanics*, **66** (2020) 1443-1460.

[2] Y. Otoguro, K. Takizawa and T.E. Tezduyar, "Space-Time VMS Computational Flow Analysis with Isogeometric Discretization and a General-Purpose NURBS Mesh Generation Method", *Computers & Fluids*, **158** (2017) 189-200.

[3] T. Kuraishi, K. Takizawa and T.E. Tezduyar, "Tire Aerodynamics with Actual Tire Geometry, Road Contact and Tire Deformation", *Computational Mechanics*, **63** (2019) 1165-1185.

[4] 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.