Research Report（April, 2019 - March, 2020）

In the SGU course of Mathematical Physical Science: April 2017-March 2020

Conferring university	Degree name (by completing a course / by thesis only)	Date of conferment
Waseda University	Doctor of Engineering (by completing a course)	03/15/2020

Enrollment from April 2017 Department of Modern Mechanical Engineering Takuya TERAHARA

I. List of Papers

1. K. Takizawa, T.E. Tezduyar, **T. Terahara**, and T. Sasaki, "Heart valve flow computation with the integrated Space–Time VMS, Slip Interface, Topology Change and Isogeometric Discretization methods", *Computers & Fluids*, **158** (2017) 176–188.
2. K. Takizawa, T.E. Tezduyar, H. Uchikawa, **T. Terahara**, T. Sasaki, and A. Yoshida, "Mesh refinement influence and cardiac-cycle flow periodicity in aorta flow analysis with isogeometric discretizations", *Computers & Fluids*, **179** (2019) 790–798.
3. K. Takizawa, T.E. Tezduyar, H. Uchikawa, T. Terahara, T. Sasaki, K. Shiozaki, A. Yoshida, K. Komiya, and G. Inoue, "Aorta flow analysis and heart valve flow and structure analysis", *Frontiers in Computational Fluid–Structure Interaction and Flow Simulation: Research from Lead Investigators under Forty – 2018* (2018) 29-89, 10.1007/978-3-319-96469-0_2.
4. **T. Terahara**, K. Takizawa, T.E. Tezduyar, M.C. Hsu, and Y. Bazilevs, "Heart valve isogeometric sequentially-coupled FSI analysis with the space–time topology change method", *Computational Mechanics*, published online, 2020.
5. **T. Terahara**, K. Takizawa, T.E. Tezduyar, "Ventricle-Valve-Aorta Flow Analysis with the Space–Time Isogeometric Discretization and Topology Change", *Computational Mechanics*, published online, 2020.

II. Record of Awards

1. **Best CFD Visualization Award,** The 33th Computational Fluid Dynamics Symposium

III. List of Talks

International Lectures

1. **T. Terahara**, K. Takizawa, T.E. Tezduyar, and T. Sasaki, "Heart valve flow analysis with the integrated Space–Time VMS, Slip Interface, and Topology Change methods and isogeometric discretization", in *Extended Abstracts of the 2017 Engineering Mechanics Institute Conference*, California, USA, 2017.
2. **T. Terahara**, K. Takizawa, and T.E. Tezduyar, "Heart valve flow analysis with the integrated space–time variational multiscale, slip interface, and topology change methods and isogeometric discretization", in *Extended Abstracts of International Workshop on the Multi-Phase Flow; Analysis, Modeling and Numerics*, Tokyo, Japan, 2017.
3. **T. Terahara**, K. Takizawa, T.E. Tezduyar, M.-C. Hsu, and Y. Bazilevs, "Heart valve sequentially-coupled FSI analysis with the ST-SI-TC-IGA", in *Proceedings of IGA 2018*, Texas, USA, 2018.
4. **T. Terahara**, K. Takizawa, T.E. Tezduyar, R. Kobayashi, and A. Tsushima, "Ventricle-valve-aorta flow analysis with the space–time isogeometric discretization and topology change", in *Proceedings of the Asian Pacific Congress on Computational Mechanics (APCOM) 2019*, Taipei, Taiwan, 2019.

Domestic Lectures

1. **T. Terahara**, K. Shiozaki, R. Kobayashi, A. Tsushima, K. Takizawa, and T.E. Tezduyar, "Space–time computational analysis of ventricle-valve-aorta flow", in *Proceedings of JSME 32th Computational Mechanics Division Conference*,

Saitama, Japan, 2019.

2. **T. Terahara**, K. Shiozaki, R. Kobayashi, A. Tsushima, K. Takizawa, and T.E. Tezduyar, "Ventricle-valve-aorta flow analysis with the ST-SI-TC-IGA", in *Proceedings of 24th Japan Society for Computational Engineering and Science Conference*, Saitama, Japan, 2019.
3. **T. Terahara**, T. Sasaki, K. Shiozaki, K. Takizawa, and T.E. Tezduyar, "Flow and structure analysis of the aortic valve", in *Extended Abstracts of the 10th Research Committee on Blood Flow and Cardiovascular System*, Nagano, Japan, 2018.
4. T. Terahra, K. Shiozaki, R. Kobayashi, A. Tsushima, K. Takizawa, T.E. Tezduyar, "Computational Analysis of the Blood Flow in the Aorta and Heart Valve with ST-SI-TC-IGA", in *Extended Abstracts of JST CREST-PRESTO-AIMaP Symposium 2019*, Tokyo, Japan, 2018.
5. **T. Terahara**, T. Sasaki, K. Shiozaki, K. Takizawa, and T.E. Tezduyar, "Aortic valve analysis based on high-fidelity computational fluid dynamics", in *Proceedings of JSME 28th Conference on Frontiers in Bioengineering*, Tokushima, Japan, 2017.
6. **T. Terahara**, K. Shiozaki, T. Sasaki, K. Takizawa, and T.E. Tezduyar, "Heart valve flow analysis with isogeometric discretization and resolved jet flow near leaflet surfaces", in *Extended Abstracts of Mechanical Engineering Congress 2017*, Saitama, Japan, 2017.

8 others

IV. Research Results in AY2019

We succeeded in a sequentially coupled FSI (SCFSI) analysis of the heart valve in 2018. The SCFSI analysis dealt with a motion from fully coupled immersogeometric FSI analysis and captured the flow solution near the leaflet surfaces accurately. This year, we applied the method for the heart valve flow analysis to realistic geometries, which include an aorta and a ventricle. Typically, in computational flow analysis, we specify the velocity at the inflow boundary and the traction at the outflow boundary. In ventricle-valve-aorta flow analysis, we specified the traction at the inflow boundary, because the flowrate should be in the solution. Generally, with the traction at the inflow boundary, the energy coming into the domain is not under control, and we could get different flow fields for the same flow rate. For this, we place a special-purpose element consisting of quadratic NURBS. The special-purpose element has only one unspecified control-point velocity at the inflow. With this, we can constrain the flow profile. We applied this technique to ventricle-valve-aorta flow analysis. The analysis gave us a more realistic flow, large vortex in the ventricle, and torsional flow in the aorta. The WSS on the leaflet surfaces got asymmetry due to the flow from the ventricle.

Summary (From April 2017 to March 2020)

The objective of the research is to introduce the computational methods for high-fidelity heart valve flow analysis. We use an interface-tracking method to obtain an accurate flow solution near the leaflet surfaces. With the interface-tracking method, a contact of leaflet surfaces causes a topology change. The space–time topology change (ST-TC) method was introduced for the topology change. However, it was not applicable to heart valve flow analysis. For this, we integrated the ST-TC method with the ST slip interface (ST-SI) method for the asymmetric leaflet motion and ST isogeometric analysis (ST-IGA) for the representation of the narrow geometries. The method is named "ST-SI-TC-IGA" and applied to several problems. We applied the ST-SI-TC-IGA to the leaflet motion from structural mechanics in 2017 and the leaflet motion from immersogeometric FSI analysis. The complicated leaflet motion makes a mesh-moving more difficult near the leaflet surfaces. For this, we generated a mesh, a part of the mesh around the leaflet surfaces is moved manually, and the rest of the mesh is moved automatically. In 2019, we combined all the methods and carried out ventricle-valve-aorta flow analysis. Here, we specified the traction at the inflow boundary. To have stability, we place a special-purpose element to constrain the flow profile. The ST-SI-TC-IGA enables us to calculate the WSS in each analysis and evaluate how the flow affects the leaflet surfaces.