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Space–time computations in practical engineering applications: a summary of the 25-year history

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Abstract
In an article published online in July 2018 it was stated that the algorithm proposed in the article is "enabling practical implementation of the space–time FEM for engineering applications." In fact, space–time computations in practical engineering applications were already enabled in 1993. We summarize the computations that have taken place since then. These computations started with finite element discretization and are now also with isogeometric discretization. They were all in 3D space and were all carried out on parallel computers. For quarter of a century, these computations brought solution to many classes of complex problems ranging from Orion spacecraft parachutes to wind turbines, from patient-specific cerebral aneurysms to heart valves, from thermo-fluid analysis of ground vehicles and tires to turbocharger turbines and exhaust manifolds.

Keywords Space–time computation · Fluid mechanics · Fluid–structure interaction · Finite element discretization · Isogeometric discretization

1 Introduction

In an article published online in July 2018 [1] it was stated in the abstract that the algorithm proposed in the article is "enabling practical implementation of the space–time FEM for engineering applications." There is a similar statement in the introduction: their "efficient solution algorithm" is "enabling practical application of [space–time FEM]." The conclusions section also has a similar statement: "An efficient iterative solution algorithm has been developed in this work that enables the practical applications of [time-discontinuous Galerkin]-based space–time FEM."

In fact, space–time computations in practical engineering applications were already enabled in 1993 [2]. They started with finite element discretization and are now also with isogeometric discretization. These computations were all in 3D space and were all carried out on parallel computers. For quarter of a century, they brought solution to many classes of complex problems ranging from Orion spacecraft parachutes to wind turbines, from patient-specific cerebral aneurysms to heart valves, from thermo-fluid analysis of ground vehicles and tires to turbocharger turbines and exhaust manifolds. We summarize these computations in the next section. We limit the summary to computations reported in journal articles indexed by the Web of Science.

2 Space–time computations in practical engineering applications

The Deforming-Spatial-Domain/Stabilized Space–Time (DSD/SST) method [3–5] was introduced for computation of flows with moving boundaries and interfaces, including fluid–structure interactions (FSI). The stabilization components of the DSD/SST are the Streamline-Upwind/Petrov-Galerkin (SUPG) [6] and Pressure-Stabilizing/Petrov-Galerkin (PSPG) [3] stabilizations. Because of the SUPG and PSPG components, the DSD/SST is now also called "ST-SUPS." The ST Variational Multiscale (ST-VMS) method [7–9] is the VMS version of the DSD/SST. The VMS com-

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ponents of the ST-VMS are from the residual-based VMS method [10–13]. The ST-SUPS and ST-VMS are quite often used with special ST methods that increase the scope and accuracy of the ST computations. These special ST methods include the ST Slip Interface (ST-SI) [14,15] and ST Topology Change (ST-TC) [16,17] methods. The ST-SUPS and ST-VMS computations started with finite element discretization, but with the ST Isogeometric Analysis (ST-IGA) [7,18,19], they are now also with isogeometric discretization in space and time. When we summarize the ST computations in practical engineering applications, we will focus on the application, rather than the precise nature of the ST computational framework. The framework might have the ST-SUPS or ST-VMS as its core component, and might include special ST methods such as ST-SI, ST-TC, ST-IGA, or the integration of all these as "ST-SI-TC-IGA" [20].

2.1 Years 1993–2000

The first ST computations in practical engineering applications in 3D space were reported in 1993 [2]. The problems solved in [2] included sloshing in a tank subjected to vertical vibrations and Taylor–Couette flow at Reynolds number 150, 250 and 1,498. The sloshing computation was also reported in a 1994 article [21]. A review article published in 1994 [22] included the sloshing problem, the Taylor–Couette flow, flow past a Los Angeles class submarine, and flow-induced vibrations of a flexible pipe. The pipe problem was also reported in a 1995 article [23], together with flapping-wing aerodynamics. The wing problem had over 1,100,000 coupled nonlinear equations solved every time step of the computation. We note that while the largest 3D problem solved in [1] had about 490,000 equations, unsteady computations with over 1,100,000 coupled equations were already enabled 23 years ago, with the hardware technology of 23 years ago.

Fluid–particle interaction computations with spheres falling in a liquid-filled tube were reported first for 2–5 spheres in 1996 [24], then for 100 spheres in 1997 [25], and then for 1000 spheres in 1999 [26]. In the computations with 1000 spheres, approximately 5.5 million coupled nonlinear equations were solved at every time step, with the hardware technology of 20 years ago.

A review article published in 1996 [27] included flow around two high-speed trains passing each other in a tunnel, longitudinal dynamics of a large ram-air parachute, flare maneuver of a large ram-air parachute, flow past a dam, fluid–particle interactions with 3 and 5 spheres, and dynamics of a paratrooper jumping from a cargo plane. The flare maneuver was also reported, in detail, in 1997 [28]. Parafoil inflation aerodynamics was reported in 1997 [29], and gas impinging on a liquid surface was also reported in 1997 [30]. Free-surface flow past a circular cylinder, with hydraulic jump, was reported in 1999 [31], and flow past a propeller was also reported in 1999 [32]. Two review articles published in 1999 [33,34] included flow around two high-speed trains in a tunnel, ram-air parachute flare maneuver, dynamics of a paratrooper jumping from a cargo plane, fluid–particle interactions of 1000 spheres falling in a liquid-filled tube, flow past a dam, free-surface flow past a circular cylinder, and aerodynamics of a parachute crossing the wake of an aircraft. Parachute FSI for a T-10 parachute was reported in 2000 [35].

2.2 Years 2001–2010

Computations reported in 2001 included aerodynamics of a helicopter [36], fluid–particle interactions in spatially periodic domains [37], parachute FSI for a cross parachute [38], aerodynamics and FSI of a parachute crossing the wake of an aircraft [39,40], and FSI of a T-10 parachute with line pull [41]. A review article published in [42] included ram-air parachute flare maneuver, flow around two high-speed trains in a tunnel, flow past a propeller, aerodynamics of a helicopter, fluid–particle interactions of 1000 spheres falling in a liquid-filled tube, fluid–particle interactions in spatially periodic cells, free-surface flow past a circular cylinder, and flow past a dam. Parachute FSI reported in 2003 included aerodynamic interactions between two parachutes [43] and parachutes with control-line inputs [44]. Soft landing of a T-10 parachute was reported in 2005 [45].

The FSI computations reported in 2006 [46–51] included T-10 parachute soft landing, flow past a flag, patient-specific internal carotid arteries, patient-specific cerebral aneurysms with normal and high blood pressure, and soft landing of a G-12 parachute. Transonic flow past a sphere was also reported in 2006 [52]. The FSI computations reported in 2007 [5,53–57] and 2008 [58–63] were for flow past a flag, patient-specific models of a middle cerebral artery with aneurysm and a birfucating middle cerebral artery with aneurysm, carotid artery birfucation, abdominal aortic aneurysms, parachutes with complex designs, a cloth piece falling over a rigid rod, flow in a tube constrained with a diaphragm, inflation of a balloon, flow through and around a windsock, descent of a T-10 parachute with fabric porosity, sails, Orion spacecraft parachutes, flow around two flexible spheres colliding, and a flexible sphere sliding past a constriction in a channel.

The FSI computations reported in 2009 [64–66] and 2010 [67–73] were for detailed parachute and artery analysis. The detailed studies were mainly on cerebral arteries with aneurysm, Orion spacecraft parachutes, and reefed stages of the Orion spacecraft parachutes.

2.3 Years 2011–2018

The computations reported in 2011 were for detailed parachute FSI analysis [74–76], arterial FSI analysis [77–81],

and wind-turbine aerodynamics [82–84]. The detailed studies included different trial canopy design configurations of the Orion spacecraft parachutes, Orion spacecraft parachute clusters with two and three parachutes, FSI-based dynamical analysis of the Orion spacecraft parachutes and parachute clusters, patient-specific cerebral arteries with aneurysm, and full-scale wind-turbine rotors.

The computations reported in 2012 were for detailed analysis of parachute FSI [85–88], arterial FSI [89,90], flow in aneurysms blocked with stent [91], wind-turbine aerodynamics [92], and bioinspired flapping-wing aerodynamics [18,93,94]. The detailed parachute studies, all for the Orion spacecraft parachutes, were for different designs of the suspension lines and overinflation control line, reefed parachute stages, different trial canopy design configurations, different payload models, 2-parachute clusters, FSI-based dynamical analysis of single parachutes and parachute clusters, disreefing of single parachutes and parachute clusters, parachutes with modified geometric porosity, and Stage 2 shape determination for the modified-geometric-porosity parachute. The artery studies included comparative studies based on patient-specific cerebral arteries with ruptured and unruptured aneurysms, FSI analysis of a number of patient-specific cerebral arteries with aneurysm, and flow analysis of patient-specific cerebral aneurysms blocked with stent. The wind-turbine aerodynamic analyses were for full-scale wind-turbine rotors. The bioinspired flapping-wing aerodynamic analyses were for an actual locust and for an MAV with the wing motion coming from an actual locust.

More computations were reported in 2013 for detailed analysis of spacecraft parachute FSI and spacecraft aerodynamics [95–97], flow in patient-specific aneurysms blocked with stent [98], flapping-wing aerodynamics of an actual locust [99], and wind-turbine rotor and tower aerodynamics at full scale [100]. The studies on spacecraft parachute FSI and spacecraft aerodynamics included forward bay cover parachute, cover separation, clusters of parachutes with modified geometric porosity, and FSI-based dynamic analysis of those parachute clusters.

The computations reported in 2014 were for bioinspired flapping-wing aerodynamics [101–103], patient-specific aneurysms blocked with stent [104], spacecraft parachute FSI [102,105], wind-turbine rotor aerodynamics and rotor and tower aerodynamics [102,103,106], FSI of cerebral arteries with aneurysm [102], and heart valve flow analysis [17]. The spacecraft parachute FSI analyses included clusters of parachutes with the original design and with modified geometry porosity, different designs of the suspension lines, disreefing of a single parachute from Stage 1 to 2 to 3, disreefing of a 2-parachute cluster from Stage 2 to 3, and a drogue parachute at Stage 1, 2 and 3 under different flight conditions. The bioinspired flapping-wing aerodynamics included an actual locust and an MAV with the wing motion coming from an actual locust.

The computations reported in 2015 and 2016 were for spacecraft parachute FSI [107,108], flapping-wing aerodynamics with wing clapping [109], thermo-fluid analysis of a truck and its tires [9], aerodynamics of a vertical-axis wind turbine [14], thermo-fluid analysis of a disk brake [15], aerodynamics of a tire with road contact and deformation [110], and ram-air parachute aerodynamics [111]. The parachute FSI computations included aerodynamic moment analysis of a single Orion spacecraft parachute, a 2-parachute cluster and JAXA subscale parachute, and detailed analysis of the Orion drogue parachute at Stage 1, 2 and 3, under different flight conditions. The truck computation (reported in 2015) had about 55 million coupled nonlinear equations solved every time step. That is more than 100 times larger than the largest 3D problem solved (490,000 equations) in [1].

The computations reported in 2017 and 2018 (first half) were for flow-driven string dynamics in turbomachinery [112], turbocharger turbine flow analysis [19], turbocharger turbine and exhaust manifold flow analysis [113,114], heart valve flow analysis [20], spacecraft parachute compressible-flow aerodynamics [115,116], and patient-specific aorta flow analysis [117].

3 Concluding remarks

We summarized the 25-year history of ST computations in a wide range of practical engineering applications, from Orion spacecraft parachutes to wind turbines, from patient-specific cerebral aneurysms to heart valves, from thermo-fluid analysis of ground vehicles and tires to turbocharger turbines and exhaust manifolds. These computations started with finite element discretization and are now also with isogeometric discretization. They were all in 3D space and were all carried out on parallel computers. We limited the summary to computations reported in journal articles indexed by the Web of Science. While the largest 3D problem solved in [1] had about half a million equations, the number of coupled nonlinear equations solved every time step in the ST computations we summarized exceeded one million as early as 23 years ago. For some of the ST computations we summarized, the number reached 55 million. We showed clearly that ST computations in practical engineering applications were already enabled 25 years ago.

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