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Numerical-performance studies for the stabilized space-time computation of wind-turbine rotor aerodynamics. (English) Zbl 1334.74032

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Summary: We present our numerical-performance studies for 3D wind-turbine rotor aerodynamics computation with the deforming-spatial-domain/stabilized space-time (DSD/SST) formulation. The computation is challenging because of the large Reynolds numbers and rotating turbulent flows, and computing the correct torque requires an accurate and meticulous numerical approach. As the test case, we use the NREL 5MW offshore baseline wind-turbine rotor. We compute the problem with both the original version of the DSD/SST formulation and the version with an advanced turbulence model. The DSD/SST formulation with the turbulence model is a recently-introduced space-time version of the residual-based variational multiscale method. We include in our comparison as reference solution the results obtained with the residual-based variational multiscale Arbitrary Lagrangian-Eulerian method using NURBS for spatial discretization. We test different levels of mesh refinement and different definitions for the stabilization parameter embedded in the "least squares on incompressibility constraint" stabilization. We compare the torque values obtained.

MSC:

74F10 Fluid-solid interactions (including aero- and hydro-elasticity, porosity, etc.)
76G25 General aerodynamics and subsonic flows
76F65 Direct numerical and large eddy simulation of turbulence

Keywords:

DSD/SST formulation; space-time variational multiscale method; wind-turbine aerodynamics; rotating turbulent flow; torque values

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References:

[1] Bazilevs Y, Hsu M-C, Akkerman I, Wright S, Takizawa K, Henicke B, Spielman T, Tezduyar TE (2011) 3D simulation of wind turbine rotors at full scale. Part I: Geometry modeling and aerodynamics. Int J Numer Methods Fluids 65: 207–235. doi: 10.1002/fld.2400 · Zbl 1428.76086 · doi:10.1002/fld.2400

[2] Bazilevs Y, Hsu M-C, Kiendl J, Wüchner R, Bletzinger K-U (2011) 3D simulation of wind turbine rotors at full scale. Part II: fluid–structure interaction modeling with composite blades. Int J Numer Methods Fluids 65: 236–253 · Zbl 1428.76087 · doi:10.1002/fld.2454

[3] Hughes TJR, Cottrell JA, Bazilevs Y (2005) Isogeometric analysis: CAD, finite elements, NURBS, exact geometry, and mesh refinement. Comput Methods Appl Mech Eng 194: 4135–4195 · Zbl 1151.74419 · doi:10.1016/j.cma.2004.10.008

[4] Tezduyar TE (1992) Stabilized finite element formulations for incompressible flow computations. Adv Appl Mech 28: 1–44. doi: 10.1016/S0065-2156(08)70153-4 · Zbl 0747.76069 · doi:10.1016/S0065-2156(08)70153-4

[5] Tezduyar TE, Behr M, Liou J (1992) A new strategy for finite element computations involving moving boundaries and interfaces – the deforming-spatial-domain/space–time procedure: I The concept and the preliminary numerical tests. Comput Methods Appl Mech Eng 94: 339–351. doi: 10.1016/0045-7825(92)90059-S · Zbl 0745.76044 · doi:10.1016/0045-7825(92)90059-S

[6] Tezduyar TE, Behr M, Mittal S, Liou J (1992) A new strategy for finite element computations involving moving boundaries and interfaces – the deforming-spatial-domain/space–time procedure: II. Computation of free-surface flows, two-liquid flows, and flows with drifting cylinders. Comput Methods Appl Mech Eng 94: 353–371. doi: 10.1016/0045-7825(92)90060-W · Zbl 0745.76045 · doi:10.1016/0045-7825(92)90060-W

[7] Tezduyar TE (2003) Computation of moving boundaries and interfaces and stabilization parameters. Int J Numer Methods Fluids 43: 555–575. doi: 10.1002/fld.505 · Zbl 1032.76605 · doi:10.1002/fld.505

[8] Tezduyar TE, Sathe S (2007) Modeling of fluid–structure interactions with the space–time finite elements: solution techniques. Int J Numer Methods Fluids 54: 855–900. doi: 10.1002/fld.1430 · Zbl 1144.74044 · doi:10.1002/fld.1430

[9] Takizawa K, Tezduyar TE, Multiscale space–time fluid–structure interaction techniques. Comput Mech. doi: 10.1007/s00466-

011-0571-z , February 2011, doi: 10.1007/s00466-011-0571-z · Zbl 1398.76128

[10] Hughes TJR (1995) Multiscale phenomena: Green's functions, the Dirichlet-to-Neumann formulation, subgrid scale models, bubbles, and the origins of stabilized methods. Comput Methods Appl Mech Eng 127: 387–401 · Zbl 0866.76044 · doi:10.1016/0045-7825(95)00844-9

[11] Hughes TJR, Oberai AA, Mazzei L (2001) Large eddy simulation of turbulent channel flows by the variational multiscale method. Phys Fluids 13: 1784–1799 · Zbl 1184.76237 · doi:10.1063/1.1367868

[12] Bazilevs Y, Calo VM, Cottrel JA, Hughes TJR, Reali A, Scovazzi G (2007) Variational multiscale residual-based turbulence modeling for large eddy simulation of incompressible flows. Comput Methods Appl Mech Eng 197: 173–201 · Zbl 1169.76352 · doi:10.1016/j.cma.2007.07.016

[13] Bazilevs Y, Akkerman I (2010) Large eddy simulation of turbulent Taylor–Couette flow using isogeometric analysis and the residual–based variational multiscale method. J Comput Phys 229: 3402–3414 · Zbl 1290.76037 · doi:10.1016/j.jcp.2010.01.008

[14] Takizawa K, Henicke B, Tezduyar TE, Hsu M-C, Bazilevs Y (2011) Stabilized space–time computation of wind-turbine rotor aerodynamics. Comput Mech. doi: 10.1007/s00466-011-0589-2 , March 2011, doi: 10.1007/s00466-011-0589-2 · Zbl 1398.76127

[15] Hughes TJR, Liu WK, Zimmermann TK (1981) Lagrangian–Eulerian finite element formulation for incompressible viscous flows. Comput Methods Appl Mech Eng 29: 329–349 · Zbl 0482.76039 · doi:10.1016/0045-7825(81)90049-9

[16] Tezduyar T, Aliabadi S, Behr M, Johnson A, Mittal S (1993) Parallel finite-element computation of 3D flows. Computer 26: 27–36. doi: 10.1109/2.237441 · Zbl 05090697 · doi:10.1109/2.237441

[17] Behr M, Johnson A, Kennedy J, Mittal S, Tezduyar T (1993) Computation of incompressible flows with implicit finite element implementations on the connection machine. Comput Methods Appl Mech Eng 108: 99–118. doi: 10.1016/0045-7825(93)90155-Q · Zbl 0784.76046 · doi:10.1016/0045-7825(93)90155-Q

[18] Tezduyar TE, Aliabadi SK, Behr M, Mittal S (1994) Massively parallel finite element simulation of compressible and incompressible flows. Comput Methods Appl Mech Eng 119: 157–177. doi: 10.1016/0045-7825(94)00082-4 · Zbl 0848.76040 · doi:10.1016/0045-7825(94)00082-4

[19] Mittal S, Tezduyar TE (1994) Massively parallel finite element computation of incompressible flows involving fluid-body interactions. Comput Methods Appl Mech Eng 112: 253–282. doi: 10.1016/0045-7825(94)90029-9 · Zbl 0846.76048 · doi:10.1016/0045-7825(94)90029-9

[20] Mittal S, Tezduyar TE (1995) Parallel finite element simulation of 3D incompressible flows–fluid–structure interactions. Int J Numer Methods Fluids 21: 933–953. doi: 10.1002/fld.1650211011 · Zbl 0873.76047 · doi:10.1002/fld.1650211011

[21] Aliabadi SK, Tezduyar TE (1995) Parallel fluid dynamics computations in aerospace applications. Int J Numer Methods Fluids 21: 783–805. doi: 10.1002/fld.1650211003 · Zbl 0862.76033 · doi:10.1002/fld.1650211003

[22] Tezduyar T, Aliabadi S, Behr M, Johnson A, Kalro V, Litke M (1996) Flow simulation and high performance computing. Comput Mech 18: 397–412. doi: 10.1007/BF00350249 · Zbl 0893.76046 · doi:10.1007/BF00350249

[23] Johnson AA, Tezduyar TE (1997) Parallel computation of incompressible flows with complex geometries. Int J Numer Methods Fluids 24:1321–1340. doi: 10.1002/(SICI)1097-0363(199706)24:12\<1321::AID-FLD562\>3.3.CO;2-C

[24] Johnson AA, Tezduyar TE (1999) Advanced mesh generation and update methods for 3D flow simulations. Comput Mech 23: 130–143. doi: 10.1007/s004660050393 · Zbl 0949.76049 · doi:10.1007/s004660050393

[25] Behr M, Tezduyar T (1999) The shear-slip mesh update method. Comput Methods Appl Mech Eng 174: 261–274. doi: 10.1016/S0045-7825(98)00299-0 · Zbl 0959.76037 · doi:10.1016/S0045-7825(98)00299-0

[26] Kalro V, Tezduyar TE (2000) A parallel 3D computational method for fluid–structure interactions in parachute systems. Comput Methods Appl Mech Eng 190: 321–332. doi: 10.1016/S0045-7825(00)00204-8 · Zbl 0993.76044 · doi:10.1016/S0045-7825(00)00204-8

[27] Stein K, Benney R, Kalro V, Tezduyar TE, Leonard J, Accorsi M (2000) Parachute fluid–structure interactions: 3-D computation. Comput Methods Appl Mech Eng 190: 373–386. doi: 10.1016/S0045-7825(00)00208-5 · Zbl 0973.76055 · doi:10.1016/S0045-7825(00)00208-5

[28] Tezduyar TE (2001) Finite element methods for flow problems with moving boundaries and interfaces. Arch Comput Methods Eng 8: 83–130. doi: 10.1007/BF02897870 · Zbl 1039.76037 · doi:10.1007/BF02897870

[29] Tezduyar T, Osawa Y (2001) Fluid–structure interactions of a parachute crossing the far wake of an aircraft. Comput Methods Appl Mech Eng 191:717–726. doi: 10.1016/S0045-7825(01)00311-5 · Zbl 1113.76407

[30] Stein K, Benney R, Tezduyar T, Potvin J (2001) Fluid–structure interactions of a cross parachute: numerical simulation. Comput Methods Appl Mech Eng 191: 673–687. doi: 10.1016/S0045-7825(01)00312-7 · Zbl 0999.76085 · doi:10.1016/S0045-7825(01)00312-7

[31] Ohayon R (2001) Reduced symmetric models for modal analysis of internal structural-acoustic and hydroelastic-sloshing systems. Comput Methods Appl Mech Eng 190: 3009–3019 · Zbl 0971.74032 · doi:10.1016/S0045-7825(00)00379-0

[32] Behr M, Tezduyar T (2001) Shear-slip mesh update in 3D computation of complex flow problems with rotating mechanical components. Comput Methods Appl Mech Eng 190: 3189–3200. doi: 10.1016/S0045-7825(00)00388-1 · Zbl 1012.76042 · doi:10.1016/S0045-7825(00)00388-1

[33] Stein K, Tezduyar T, Benney R (2003) Mesh moving techniques for fluid–structure interactions with large displacements. J Appl Mech 70: 58–63. doi: 10.1115/1.1530635 · Zbl 1110.74689 · doi:10.1115/1.1530635

[34] Stein K, Tezduyar TE, Benney R (2004) Automatic mesh update with the solid-extension mesh moving technique. Comput Methods Appl Mech Eng 193: 2019–2032. doi: 10.1016/j.cma.2003.12.046 · Zbl 1067.74587 · doi:10.1016/j.cma.2003.12.046

[35] van Brummelen EH, de Borst R (2005) On the nonnormality of subiteration for a fluid–structure interaction problem. SIAM J Scientific Comput 27: 599–621 · Zbl 1136.65334 · doi:10.1137/S1064827503431430

[36] Tezduyar TE, Sathe S, Keedy R, Stein K (2006) Space–time finite element techniques for computation of fluid–structure interactions. Comput Methods Appl Mech Eng 195: 2002–2027. doi: 10.1016/j.cma.2004.09.014 · Zbl 1118.74052 · doi:10.1016/j.cma.2004.09.014

[37] Tezduyar TE, Sathe S, Stein K (2006) Solution techniques for the fully-discretized equations in computation of fluid– structure interactions with the space–time formulations. Comput Methods Appl Mech Eng 195: 5743–5753. doi: 10.1016/j.cma.2005.08.023 · Zbl 1123.76035 · doi:10.1016/j.cma.2005.08.023

[38] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2006) Computer modeling of cardiovascular fluid–structure interactions with the deforming-spatial-domain/stabilized space–time formulation. Comput Methods Appl Mech Eng 195: 1885–1895. doi: 10.1016/j.cma.2005.05.050 · Zbl 1178.76241 · doi:10.1016/j.cma.2005.05.050

[39] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2006) Fluid–structure interaction modeling of aneurysmal conditions with high and normal blood pressures. Comput Mech 38: 482–490. doi: 10.1007/s00466-006-0065-6 · Zbl 1160.76061 · doi:10.1007/s00466-006-0065-6

[40] Bazilevs Y, Calo VM, Zhang Y, Hughes TJR (2006) Isogeometric fluid–structure interaction analysis with applications to arterial blood flow. Comput Mech 38: 310–322 · Zbl 1161.74020 · doi:10.1007/s00466-006-0084-3

[41] Khurram RA, Masud A (2006) A multiscale/stabilized formulation of the incompressible Navier–Stokes equations for moving boundary flows and fluid–structure interaction. Comput Mech 38: 403–416 · Zbl 1184.76720 · doi:10.1007/s00466-006-0059-4

[42] Tezduyar TE (2007) Finite elements in fluids: stabilized formulations and moving boundaries and interfaces. Comput Fluids 36: 191–206. doi: 10.1016/j.compfluid.2005.02.011 · Zbl 1177.76202 · doi:10.1016/j.compfluid.2005.02.011

[43] Tezduyar TE, Sathe S, Cragin T, Nanna B, Conklin BS, Pausewang J, Schwaab M (2007) Modeling of fluid–structure interactions with the space–time finite elements: Arterial fluid mechanics. Int J Numer Methods Fluids 54: 901–922. doi: 10.1002/fld.1443 · Zbl 1276.76043 · doi:10.1002/fld.1443

[44] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2007) Influence of wall elasticity in patient-specific hemodynamic simulations. Comput Fluids 36: 160–168. doi: 10.1016/j.compfluid.2005.07.014 · Zbl 1113.76105 · doi:10.1016/j.compfluid.2005.07.014

[45] Sawada T, Hisada T (2007) Fluid–structure interaction analysis of the two dimensional flag-in-wind problem by an interface tracking ALE finite element method. Comput Fluids 36: 136–146 · Zbl 1181.76099 · doi:10.1016/j.compfluid.2005.06.007

[46] Takizawa K, Yabe T, Tsugawa Y, Tezduyar TE, Mizoe H (2007) Computation of free–surface flows and fluid–object interactions with the CIP method based on adaptive meshless Soroban grids. Comput Mech 40: 167–183. doi: 10.1007/s00466-006-0093-2 · Zbl 1177.76300 · doi:10.1007/s00466-006-0093-2

[47] Takizawa K, Tanizawa K, Yabe T, Tezduyar TE (2007) Ship hydrodynamics computations with the CIP method based on adaptive Soroban grids. Int J Numer Methods Fluids 54: 1011–1019. doi: 10.1002/fld.1466 · Zbl 1375.76153 · doi:10.1002/fld.1466

[48] Yabe T, Takizawa K, Tezduyar TE, Im H-N (2007) Computation of fluid–solid and fluid–fluid interfaces with the CIP method based on adaptive Soroban grids–an overview. Int J Numer Methods Fluids 54: 841–853. doi: 10.1002/fld.1473 · Zbl 1375.76154 · doi:10.1002/fld.1473

[49] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2007) Numerical investigation of the effect of hypertensive blood pressure on cerebral aneurysm–dependence of the effect on the aneurysm shape. Int J Numer Methods Fluids 54: 995–1009. doi: 10.1002/fld.1497 · Zbl 1317.76107 · doi:10.1002/fld.1497

[50] Manguoglu M, Sameh AH, Tezduyar TE, Sathe S (2008) A nested iterative scheme for computation of incompressible flows in long domains. Comput Mech 43: 73–80. doi: 10.1007/s00466-008-0276-0 · Zbl 1279.76024 · doi:10.1007/s00466-008-0276-0

[51] Tezduyar TE, Sathe S, Pausewang J, Schwaab M, Christopher J, Crabtree J (2008) Interface projection techniques for fluid–structure interaction modeling with moving-mesh methods. Comput Mech 43: 39–49. doi: 10.1007/s00466-008-0261-7 · Zbl 1310.74049 · doi:10.1007/s00466-008-0261-7

[52] Tezduyar TE, Sathe S, Pausewang J, Schwaab M, Christopher J, Crabtree J (2008) Fluid–structure interaction modeling of ringsail parachutes. Comput Mech 43: 133–142. doi: 10.1007/s00466-008-0260-8 · Zbl 1209.74022 · doi:10.1007/s00466-008-0260-8

[53] Tezduyar TE, Sathe S, Schwaab M, Conklin BS (2008) Arterial fluid mechanics modeling with the stabilized space–time fluid–structure interaction technique. Int J Numer Methods Fluids 57: 601–629. doi: 10.1002/fld.1633 · Zbl 1230.76054 · doi:10.1002/fld.1633

[54] Sathe S, Tezduyar TE (2008) Modeling of fluid–structure interactions with the space–time finite elements: contact problems. Comput Mech 43: 51–60. doi: 10.1007/s00466-008-0299-6 · Zbl 1297.74129 · doi:10.1007/s00466-008-0299-6

[55] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2008) Fluid–structure interaction modeling of a patient-specific cerebral aneurysm: influence of structural modeling. Comput Mech 43: 151–159. doi: 10.1007/s00466-008-0325-8 · Zbl 1169.74032 · doi:10.1007/s00466-008-0325-8

[56] Bazilevs Y, Calo VM, Hughes TJR, Zhang Y (2008) Isogeometric fluid–structure interaction: theory, algorithms, and computations. Comput Mech 43: 3–37 · Zbl 1169.74015 · doi:10.1007/s00466-008-0315-x

[57] Isaksen JG, Bazilevs Y, Kvamsdal T, Zhang Y, Kaspersen JH, Waterloo K, Romner B, Ingebrigtsen T (2008) Determination of wall tension in cerebral artery aneurysms by numerical simulation. Stroke 39: 3172–3178· doi:10.1161/STROKEAHA.107.503698

[58] Dettmer WG, Peric D (2008) On the coupling between fluid flow and mesh motion in the modelling of fluid–structure interaction. Comput Mech 43: 81–90 · Zbl 1235.74272 · doi:10.1007/s00466-008-0254-6

[59] Bazilevs Y, Hughes TJR (2008) NURBS-based isogeometric analysis for the computation of flows about rotating components. Comput Mech 43: 143–150 · Zbl 1171.76043 · doi:10.1007/s00466-008-0277-z

[60] Tezduyar TE, Schwaab M, Sathe S (2009) Sequentially-coupled arterial fluid–structure interaction (SCAFSI) technique. Comput Methods Appl Mech Eng 198: 3524–3533. doi: 10.1016/j.cma.2008.05.024 · Zbl 1229.74100 · doi:10.1016/j.cma.2008.05.024

[61] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2009) Fluid–structure interaction modeling of blood flow and

cerebral aneurysm: significance of artery and aneurysm shapes. Comput Methods Appl Mech Eng 198: 3613–3621. doi: 10.1016/j.cma.2008.08.020 · Zbl 1229.74101 · doi:10.1016/j.cma.2008.08.020

[62] Manguoglu M, Sameh AH, Saied F, Tezduyar TE, Sathe S (2009) Preconditioning techniques for nonsymmetric linear systems in computation of incompressible flows. J Appl Mech 76: 021204. doi: 10.1115/1.3059576· doi:10.1115/1.3059576

[63] Bazilevs Y, Gohean JR, Hughes TJR, Moser RD, Zhang Y (2009) Patient-specific isogeometric fluid–structure interaction analysis of thoracic aortic blood flow due to implantation of the Jarvik 2000 left ventricular assist device. Comput Methods Appl Mech Eng 198: 3534–3550 · Zbl 1229.74096 · doi:10.1016/j.cma.2009.04.015

[64] Bazilevs Y, Hsu M-C, Benson D, Sankaran S, Marsden A (2009) Computational fluid–structure interaction: methods and application to a total cavopulmonary connection. Comput Mech 45: 77–89 · Zbl 1398.92056 · doi:10.1007/s00466-009-0419-y

[65] Takizawa K, Christopher J, Tezduyar TE, Sathe S (2010) Space–time finite element computation of arterial fluid–structure interactions with patient-specific data. Int J Numer Methods Biomed Eng 26: 101–116. doi: 10.1002/cnm.1241 · Zbl 1180.92023 · doi:10.1002/cnm.1241

[66] Takizawa K, Moorman C, Wright S, Christopher J, Tezduyar TE (2010) Wall shear stress calculations in space–time finite element computation of arterial fluid–structure interactions. Comput Mech 46: 31–41. doi: 10.1007/s00466-009-0425-0 · Zbl 1301.92019 · doi:10.1007/s00466-009-0425-0

[67] Tezduyar TE, Takizawa K, Moorman C, Wright S, Christopher J (2010) Multiscale sequentially-coupled arterial FSI technique. Comput Mech 46: 17–29. doi: 10.1007/s00466-009-0423-2 · Zbl 1261.92010 · doi:10.1007/s00466-009-0423-2

[68] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2010) Influence of wall thickness on fluid–structure interaction computations of cerebral aneurysms. Int J Numer Methods Biomed Eng 26: 336–347. doi: 10.1002/cnm.1289 · Zbl 1183.92050 · doi:10.1002/cnm.1289

[69] Manguoglu M, Takizawa K, Sameh AH, Tezduyar TE (2010) Solution of linear systems in arterial fluid mechanics computations with boundary layer mesh refinement. Comput Mech 46: 83–89. doi: 10.1007/s00466-009-0426-z · Zbl 1301.76087 · doi:10.1007/s00466-009-0426-z

[70] Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE (2010) Role of 0D peripheral vasculature model in fluid–structure interaction modeling of aneurysms. Comput Mech 46: 43–52. doi: 10.1007/s00466-009-0439-7 · Zbl 1301.92020 · doi:10.1007/s00466-009-0439-7

[71] Bazilevs Y, Hsu M-C, Zhang Y, Wang W, Liang X, Kvamsdal T, Brekken R, Isaksen J (2010) A fully-coupled fluid–structure interaction simulation of cerebral aneurysms. Comput Mech 46: 3–16 · Zbl 1301.92014 · doi:10.1007/s00466-009-0421-4

[72] Tezduyar TE, Takizawa K, Moorman C, Wright S, Christopher J (2010) Space–time finite element computation of complex fluid–structure interactions. Int J Numer Methods Fluids 64: 1201–1218. doi: 10.1002/fld.2221 · Zbl 1427.76148 · doi:10.1002/fld.2221

[73] Bazilevs Y, Hsu M-C, Zhang Y, Wang W, Kvamsdal T, Hentschel S, Isaksen J (2010) Computational fluid–structure interaction: methods and application to cerebral aneurysms. Biomech Model Mechanobiol 9: 481–498· doi:10.1007/s10237-010-0189-7

[74] Kiendl J, Bazilevs Y, Hsu M-C, Wüchner R, Bletzinger K-U (2010) The bending strip method for isogeometric analysis of Kirchhoff–Love shell structures comprised of multiple patches. Comput Methods Appl Mech Eng 199: 2403–2416 · Zbl 1231.74482 · doi:10.1016/j.cma.2010.03.029

[75] Takizawa K, Moorman C, Wright S, Spielman T, Tezduyar TE (2011) Fluid–structure interaction modeling and performance analysis of the Orion spacecraft parachutes. Int J Numer Methods Fluids 65: 271–285. doi: 10.1002/fld.2348 · Zbl 1428.76011 · doi:10.1002/fld.2348

[76] Takizawa K, Moorman C, Wright S, Purdue J, McPhail T, Chen PR, Warren J, Tezduyar TE (2011) Patient-specific arterial fluid–structure interaction modeling of cerebral aneurysms. Int J Numer Methods Fluids 65: 308–323. doi: 10.1002/fld.2360 · Zbl 1203.92044 · doi:10.1002/fld.2360

[77] Takizawa K, Wright S, Moorman C, Tezduyar TE (2011) Fluid–structure interaction modeling of parachute clusters. Int J Numer Methods Fluids 65: 286–307. doi: 10.1002/fld.2359 · Zbl 1426.76312 · doi:10.1002/fld.2359

[78] Manguoglu M, Takizawa K, Sameh AH, Tezduyar TE (2011) Nested and parallel sparse algorithms for arterial fluid mechanics computations with boundary layer mesh refinement. Int J Numer Methods Fluids 65: 135–149. doi: 10.1002/fld.2415 · Zbl 1427.76285 · doi:10.1002/fld.2415

[79] Tezduyar TE, Takizawa K, Brummer T, Chen PR (2011) Space–time fluid–structure interaction modeling of patient-specific cerebral aneurysms. Int. J. Numer. Methods Biomed. Eng. doi: 10.1002/cnm.1433 · Zbl 1244.92036

[80] Takizawa K, Spielman T, Tezduyar TE (2011) Space–time FSI modeling and dynamical analysis of spacecraft parachutes and parachute clusters. Comput. Mech. doi: 10.1007/s00466-011-0590-9 · Zbl 1398.74095

[81] Takizawa K, Spielman T, Moorman C, Tezduyar TE (2011) Fluid–structure interaction modeling of spacecraft parachutes for simulation-based design. J Appl Mech (to appear) · Zbl 1428.76011

[82] Takizawa K, Brummer T, Tezduyar TE, Chen PR (2011) A comparative study based on patient-specific fluid–structure interaction modeling of cerebral aneurysms. J Appl Mech (to appear) · Zbl 1244.92036

[83] Takizawa K, Henicke B, Puntel A, Spielman T, Tezduyar TE (2011) Space–time computational techniques for the aerodynamics of flapping wings. J Appl Mech (to appear)

[84] Tezduyar T, Aliabadi S, Behr M (1998) Enhanced-discretization interface-capturing technique (EDICT) for computation of unsteady flows with interfaces. Comput Methods Appl Mech Eng 155: 235–248. doi: 10.1016/S0045-7825(97)00194-1 · Zbl 0961.76046 · doi:10.1016/S0045-7825(97)00194-1

[85] Akin JE, Tezduyar TE, Ungor M (2007) Computation of flow problems with the mixed interface-tracking/interface-capturing technique (MITICT). Comput Fluids 36: 2–11. doi: 10.1016/j.compfluid.2005.07.008 · Zbl 1181.76105 · doi:10.1016/j.compfluid.2005.07.008

[86] Cruchaga MA, Celentano DJ, Tezduyar TE (2007) A numerical model based on the mixed interface-tracking/interface-capturing technique (mitict) for flows with fluid–solid and fluid–fluid interfaces. Int J Numer Methods Fluids 54: 1021–1030. doi: 10.1002/fld.1498 · Zbl 1128.76033 · doi:10.1002/fld.1498

[87] Brooks AN, Hughes TJR (1982) Streamline upwind/Petrov- Galerkin formulations for convection dominated flows with particular emphasis on the incompressible Navier–Stokes equations. Comput Methods Appl Mech Eng 32: 199–259 · Zbl 0497.76041 · doi:10.1016/0045-7825(82)90071-8

[88] Tezduyar TE, Mittal S, Ray SE, Shih R (1992) Incompressible flow computations with stabilized bilinear and linear equal-order-interpolation velocity–pressure elements. Comput Methods Appl Mech Eng 95: 221–242. doi: 10.1016/0045-7825(92)90141-6 · Zbl 0756.76048 · doi:10.1016/0045-7825(92)90141-6

[89] Tezduyar TE, Park YJ (1986) Discontinuity capturing finite element formulations for nonlinear convection–diffusion–reaction equations. Comput Methods Appl Mech Eng 59: 307–325. doi: 10.1016/0045-7825(86)90003-4 · Zbl 0593.76096 · doi:10.1016/0045-7825(86)90003-4

[90] Tezduyar TE, Osawa Y (2000) Finite element stabilization parameters computed from element matrices and vectors. Comput Methods Appl Mech Eng 190: 411–430. doi: 10.1016/S0045-7825(00)00211-5 · Zbl 0973.76057 · doi:10.1016/S0045-7825(00)00211-5

[91] Akin JE, Tezduyar T, Ungor M, Mittal S (2003) Stabilization parameters and Smagorinsky turbulence model. J Appl Mech 70: 2–9. doi: 10.1115/1.1526569 · Zbl 1110.74311 · doi:10.1115/1.1526569

[92] Akin JE, Tezduyar TE (1922) Calculation of the advective limit of the SUPG stabilization parameter for linear and higher-order elements. Comput Methods Appl Mech Eng 193: 1909–1922. doi: 10.1016/j.cma.2003.12.050 · Zbl 1067.76557 · doi:10.1016/j.cma.2003.12.050

[93] Catabriga L, Coutinho ALGA, Tezduyar TE (2005) Compressible flow SUPG parameters computed from element matrices. Commun Numer Methods Eng 21: 465–476. doi: 10.1002/cnm.759 · Zbl 1329.76161 · doi:10.1002/cnm.759

[94] Corsini A, Rispoli F, Santoriello A, Tezduyar TE (2006) Improved discontinuity-capturing finite element techniques for reaction effects in turbulence computation. Comput Mech 38: 356–364. doi: 10.1007/s00466-006-0045-x · Zbl 1177.76192 · doi:10.1007/s00466-006-0045-x

[95] Catabriga L, Coutinho ALGA, Tezduyar TE (2006) Compressible flow SUPG parameters computed from degree-of-freedom submatrices. Comput Mech 38: 334–343. doi: 10.1007/s00466-006-0033-1 · Zbl 1176.76061 · doi:10.1007/s00466-006-0033-1

[96] Rispoli F, Corsini A, Tezduyar TE (2007) Finite element computation of turbulent flows with the discontinuity-capturing directional dissipation (DCDD). Comput Fluids 36: 121–126. doi: 10.1016/j.compfluid.2005.07.004 · Zbl 1181.76098 · doi:10.1016/j.compfluid.2005.07.004

[97] Catabriga L, de Souza DAF, Coutinho ALGA, Tezduyar TE (2009) Three-dimensional edge-based SUPG computation of inviscid compressible flows with YZ{\(\beta\)} shock-capturing. J Appl Mech 76: 021208. doi: 10.1115/1.3062968· doi:10.1115/1.3062968

[98] Corsini A, Iossa C, Rispoli F, Tezduyar TE (2010) A DRD finite element formulation for computing turbulent reacting flows in gas turbine combustors. Comput Mech 46: 159–167. doi: 10.1007/s00466-009-0441-0 · Zbl 1301.76045 · doi:10.1007/s00466-009-0441-0

[99] Hsu M-C, Bazilevs Y, Calo VM, Tezduyar TE, Hughes TJR (2010) Improving stability of stabilized and multiscale formulations in flow simulations at small time steps. Comput Methods Appl Mech Eng 199: 828–840. doi: 10.1016/j.cma.2009.06.019 · Zbl 1406.76028 · doi:10.1016/j.cma.2009.06.019

[100] Corsini A, Rispoli F, Tezduyar TE (2011) Stabilized finite element computation of NOx emission in aero-engine combustors. Int J Numer Methods Fluids 65: 254–270. doi: 10.1002/fld.2451 · Zbl 1426.76240 · doi:10.1002/fld.2451

[101] Jonkman J, Butterfield S, Musial W, Scott G (2009) Definition of a 5-MW reference wind turbine for offshore system development. Technical Report NREL/TP-500-38060, National Renewable Energy Laboratory (2009)

[102] Spera DA (1994) Introduction to modern wind turbines. In: Spera DA (eds) Wind turbine technology: fundamental concepts of wind turbine engineering. ASME Press, New Jersey, pp 47–72

[103] Saad Y, Schultz M (1986) GMRES: a generalized minimal residual algorithm for solving nonsymmetric linear systems. SIAM J Scientific Statist Comput 7: 856–869 · Zbl 0599.65018 · doi:10.1137/0907058

[104] Karypis G, Kumar V (1998) A fast and high quality multilevel scheme for partitioning irregular graphs. SIAM J Scientific Comput 20: 359–392 · Zbl 0915.68129 · doi:10.1137/S1064827595287997