Isogeometric B-Rep analysis in partitioned fluid-structure interaction with application to aeroelastic wind turbine simulations

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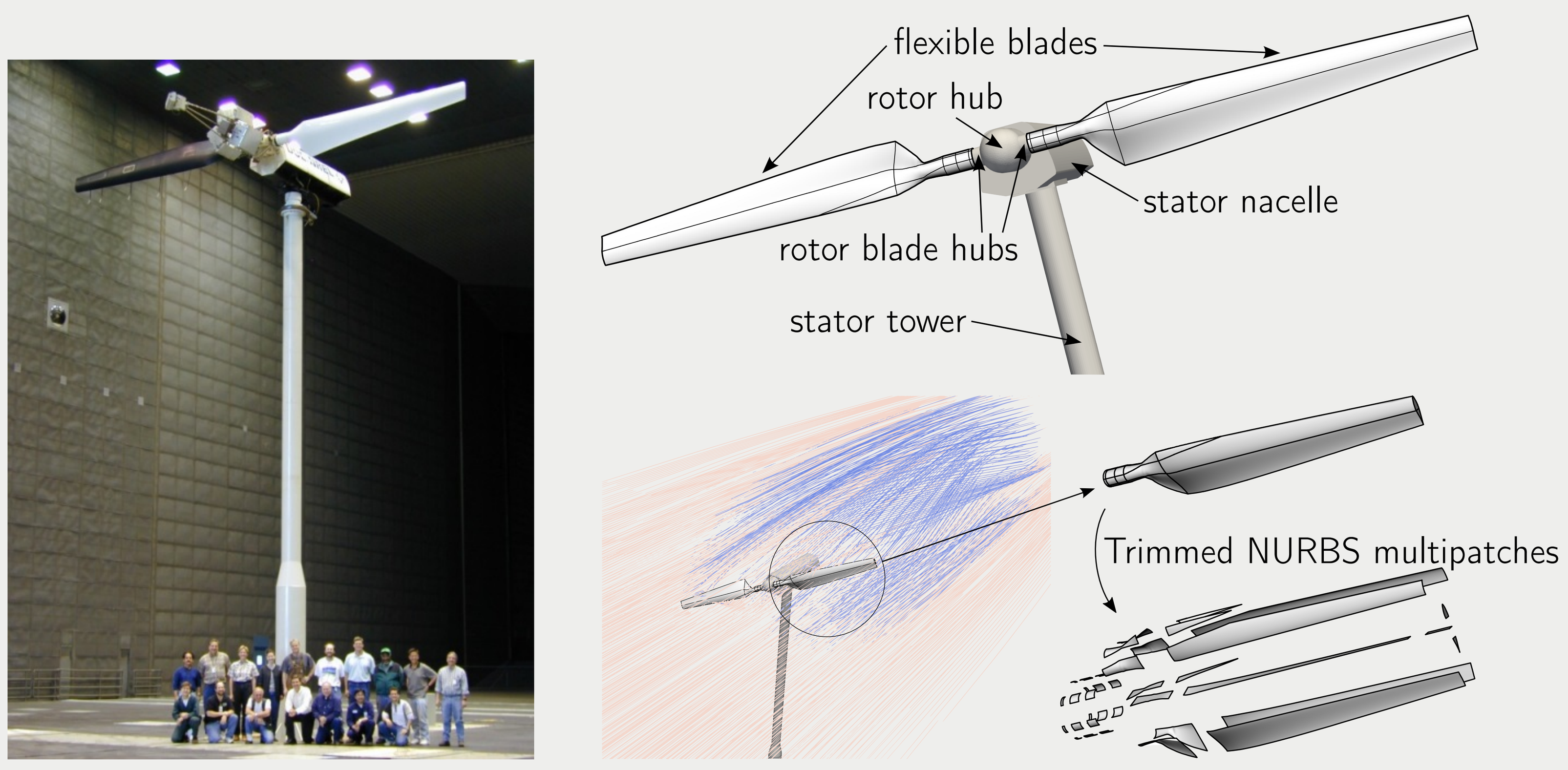
Isogeometric B-Rep computational model of the NREL phase VI wind turbine blades

Shells are playing an important role in engineering design as they demonstrate excellent load carrying capacity. Especially beneficial for thin shells is the Kirchhoff-Love shell model which is purely displacement-based, see in [1]. *Isogeometric analysis* (IGA) (firstly introduced in [2]) is a recent numerical method for solving *Partial Differential Equations* (PDEs) using the exact geometric information for the discretization of the unknown fields. It is challenging to numerically solve Kirchhoff-Love shell problems using the "classical" *Finite Element Method* (FEM) which typically uses C^0-continuous low order polynomial basis functions. This is due to the high variational index that the weak form of the Kirchhoff-Love shell problem has. However, IGA is perfectly suitable for its application to this kind of problems since the underlying *Non-Uniform Rational B-Spline* (NURBS) basis functions are typically smooth [3].



(a) NREL phase VI wind turbine [4]. (b) CAD modelling and FSI simulation using B-Rep model.

Figure 1: Picture, CAD and computational B-Rep model of the NREL phase VI wind turbine with flexible blades.

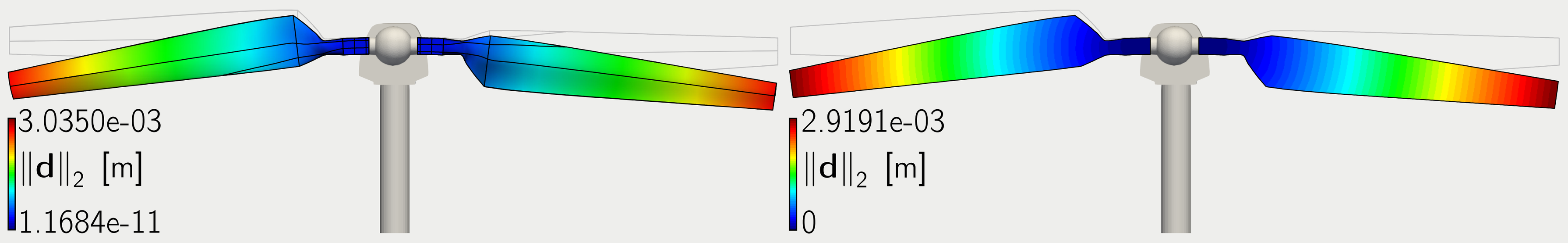
In this work, focus is put on modelling and Kirchhoff-Love shell structural analysis of wind turbines, such as the NREL phase VI wind turbine in Fig. 1(a), using the exact *Computer-Aided Design* (CAD) description of the underlying geometries utilizing the *Isogeometric B-Rep Analysis* (IBRA) [5]. IBRA is an extension of IGA on real-world CAD geometries consisting of trimmed multipatch NURBS models, as typical in modern CAD systems. Moreover, the extension of partitioned *Fluid-Structure Interaction* (FSI) simulation using wind turbines numerically discretized by means of IBRA is demonstrated, thus extending the analysis on industrial-scale CAD geometries to multiphysics problems, see Fig. 1(b).

Static and modal analyses of the flexible NREL phase VI wind turbine blades

Aiming to perform analysis directly on industrial-scale CAD geometries $\Omega \subset \mathbb{R}^3$, trimmed multipatches need to be addressed. The continuity of the solution between the multiple patches $\Omega^{(i)}$, $i = 1, \dots, n$ where $\Omega = \cup_{i=1}^{n}\Omega^{(i)}$ needs to be enforced weakly along their common interface γ_i [6, 7] and therefore, the Penalty method is employed for IBRA. The weak form of the Kirchhoff-Love shell BVP then writes: Find the displacement field $\mathbf{d} \in \boldsymbol{\mathcal{H}}^2\left(\cup_{i=1}^{n}\Omega^{(i)}\right)$ (square integrable vector-valued functions with square integrable up to second order derivatives) at each time $t \in \mathbb{T}$ such that,

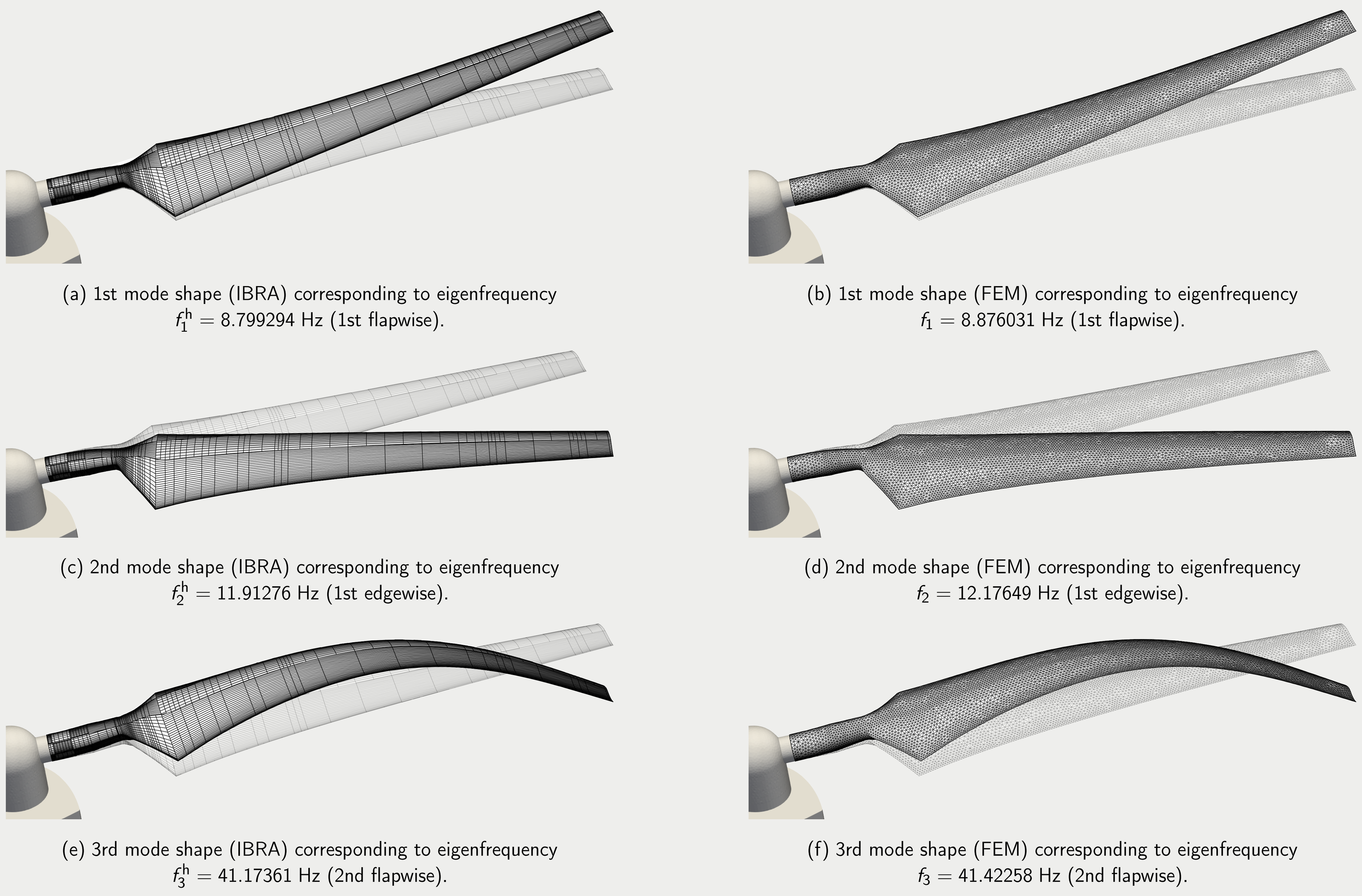
$$\sum_{i=1}^{n}\int_{\Omega^{(i)}} \rho\,\delta\mathbf{d}\cdot\ddot{\mathbf{d}}\,\bar{h} + \delta\boldsymbol{\epsilon}:\mathbf{n} + \delta\boldsymbol{\kappa}:\mathbf{m}\,\mathrm{d}\Omega + \int_{\gamma_i}\hat{\alpha}\,\delta\hat{\boldsymbol{\chi}}\cdot\hat{\boldsymbol{\chi}} + \tilde{\alpha}\,\delta\tilde{\boldsymbol{\chi}}\cdot\tilde{\boldsymbol{\chi}}\,\mathrm{d}\gamma + \int_{\Gamma_{\mathrm{d}}}\bar{\alpha}\,\delta\mathbf{d}\cdot\mathbf{d}\,\mathrm{d}\Gamma = \int_{\Omega}\delta\mathbf{d}\cdot\mathbf{b}\,\mathrm{d}\Omega\,, \qquad (1)$$

for all $\delta\mathbf{d} \in \boldsymbol{\mathcal{H}}^2\left(\cup_{i=1}^{n}\Omega^{(i)}\right)$, $\hat{\boldsymbol{\chi}}$ and $\tilde{\boldsymbol{\chi}}$ being the jump of the interface displacement and rotation field, respectively. The Dirichlet boundary conditions along Γ_{d} are imposed herein weakly because in this way, they can be defined along trimming curves. The values of the Penalty parameters $\hat{\alpha}, \tilde{\alpha}, \bar{\alpha}$ are chosen as scaling of the material and geometric constants of the problem (Young's modulus, Poisson ratio, thickness) with the minimum element edge sizes along the corresponding trimming curves where the conditions are defined.



(a) Solution using the computational IBRA model. (b) Classical Finite Element solution.

Figure 2: Contour of the displacement fields (2-norm) under self-weight of the blades over the current configuration scaled by 200.



(a) 1st mode shape (IBRA) corresponding to eigenfrequency $f_1^{\mathrm{h}} = 8.799294$ Hz (1st flapwise).

(b) 1st mode shape (FEM) corresponding to eigenfrequency $f_1 = 8.876031$ Hz (1st flapwise).

(c) 2nd mode shape (IBRA) corresponding to eigenfrequency $f_2^{\mathrm{h}} = 11.91276$ Hz (1st edgewise).

(d) 2nd mode shape (FEM) corresponding to eigenfrequency $f_2 = 12.17649$ Hz (1st edgewise).

(e) 3rd mode shape (IBRA) corresponding to eigenfrequency $f_3^{\mathrm{h}} = 41.17361$ Hz (2nd flapwise).

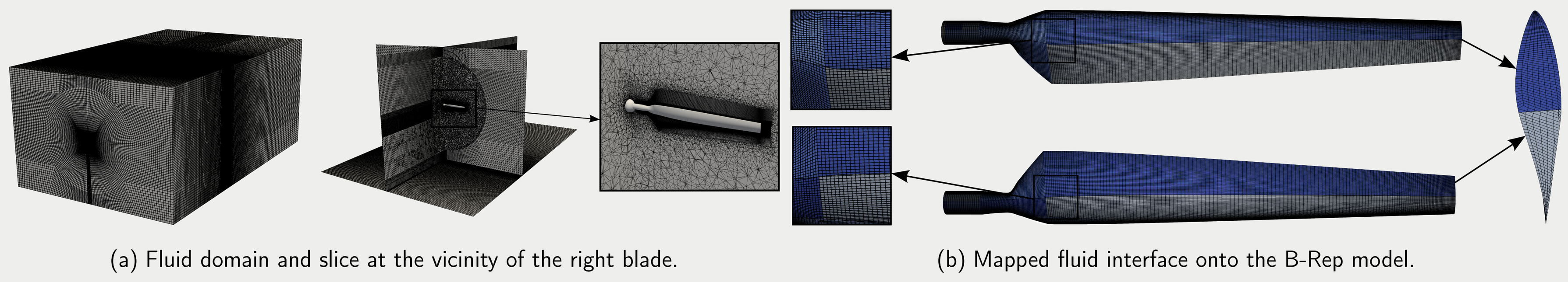
(f) 3rd mode shape (FEM) corresponding to eigenfrequency $f_3 = 41.42258$ Hz (2nd flapwise).

Figure 3: First three mode shapes with their corresponding eigenfrequencies for both the FEM and IGA on multipatches with Penalty models.

A FEM model with Reissner-Mindlin kinematics is chosen as reference solution for the evaluation of the results obtained with IBRA. The displacement magnitude over the scaled deformed configuration of the NREL phase VI wind turbine with flexible blades under its self-weight for both computational models is shown in Fig. 2. Then, the first three eigenmode shapes corresponding to eigenfrequency analysis of the right blade of the NREL phase VI wind turbine for both computational models are shown in Fig. 3, demonstrating excellent agreement between both numerical approaches.

NREL phase VI wind turbine with flexible blades in fluid-structure interaction

The partitioned FSI simulation of the NREL wind turbine with flexible blades in the numerical wind tunnel (Fig. 4(a)), according to [8], is chosen for the demonstration of the coupled FSI simulation of an IBRA computational structural model. The fluid flow is modelled by the incompressible *Unsteady Reynolds-Averaged Navier-Stokes Equations* (uRANS) [9] and numerically solved using the *Finite Volume Method* (FVM) in OpenFOAM® open source software.



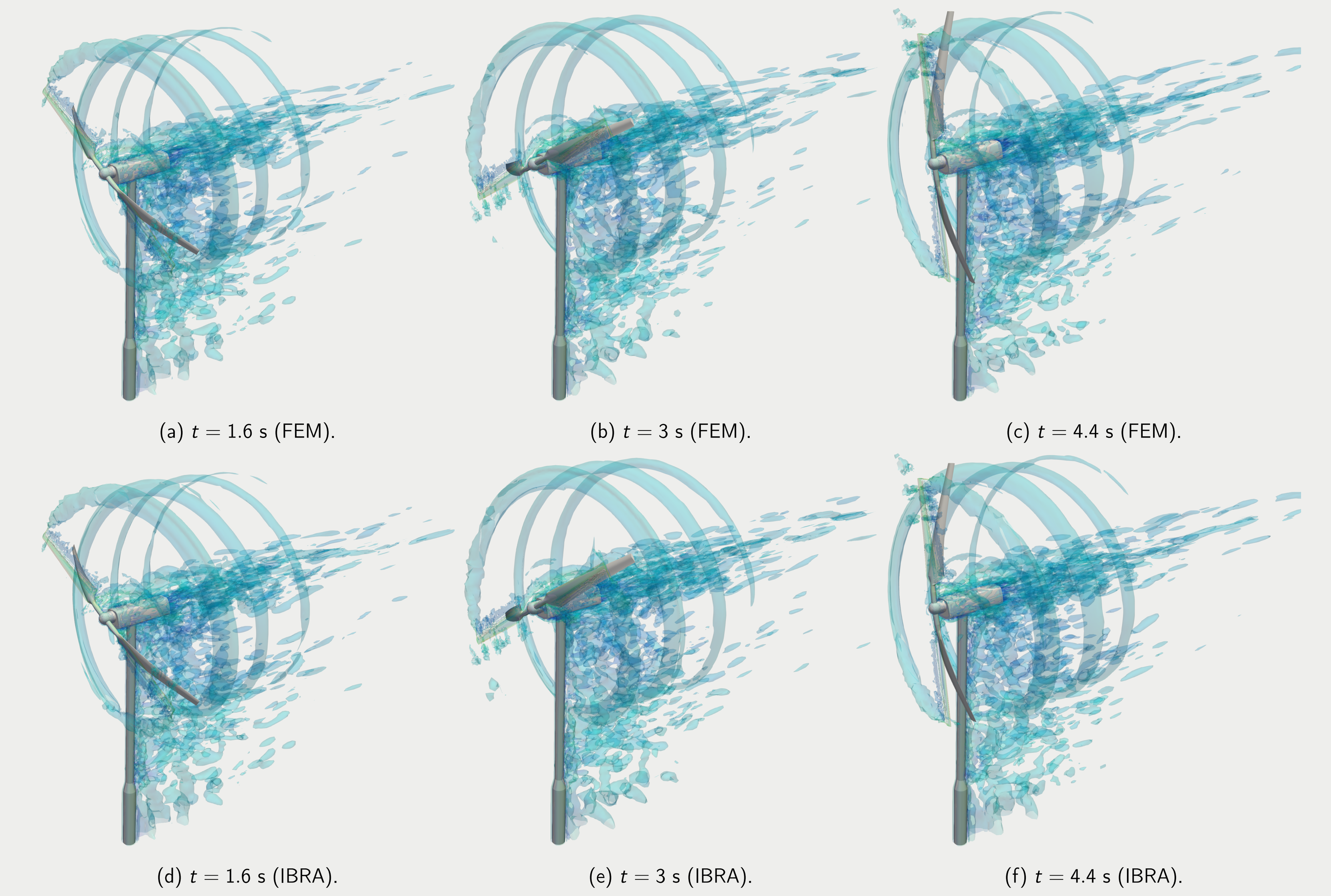
(a) Fluid domain and slice at the vicinity of the right blade. (b) Mapped fluid interface onto the B-Rep model.

Figure 4: Fluid domain and mapped fluid interface Finite Volume faces onto the B-Rep computational model.

An isogeometric mortar-based mapping method is developed for transformation of fields between the low-order discretized fluid FSI interface $\mathscr{S}_{\mathrm{h}}$ and the trimmed multipatch model of the structural FSI interface $\mathscr{S}$: Given a field $\boldsymbol{v}_{\mathrm{h}} \in \boldsymbol{P}\left(\mathscr{S}_{\mathrm{h}}\right)$ (piecewise continuous polynomial vector-valued functions), find a field $\boldsymbol{v} \in \boldsymbol{\mathcal{L}}^2\left(\mathscr{S}\right)$ (square integrable vector-valued functions) such that,

$$\int_{\mathscr{S}} \delta\boldsymbol{v}\cdot\boldsymbol{v}\,\mathrm{d}\mathscr{S} = \int_{\mathscr{S}} \delta\boldsymbol{v}\cdot\boldsymbol{v}_{\mathrm{h}}\,\mathrm{d}\mathscr{S}\,, \quad \text{for all } \delta\boldsymbol{v} \in \boldsymbol{\mathcal{L}}^2\left(\mathscr{S}\right)\,. \qquad (2)$$

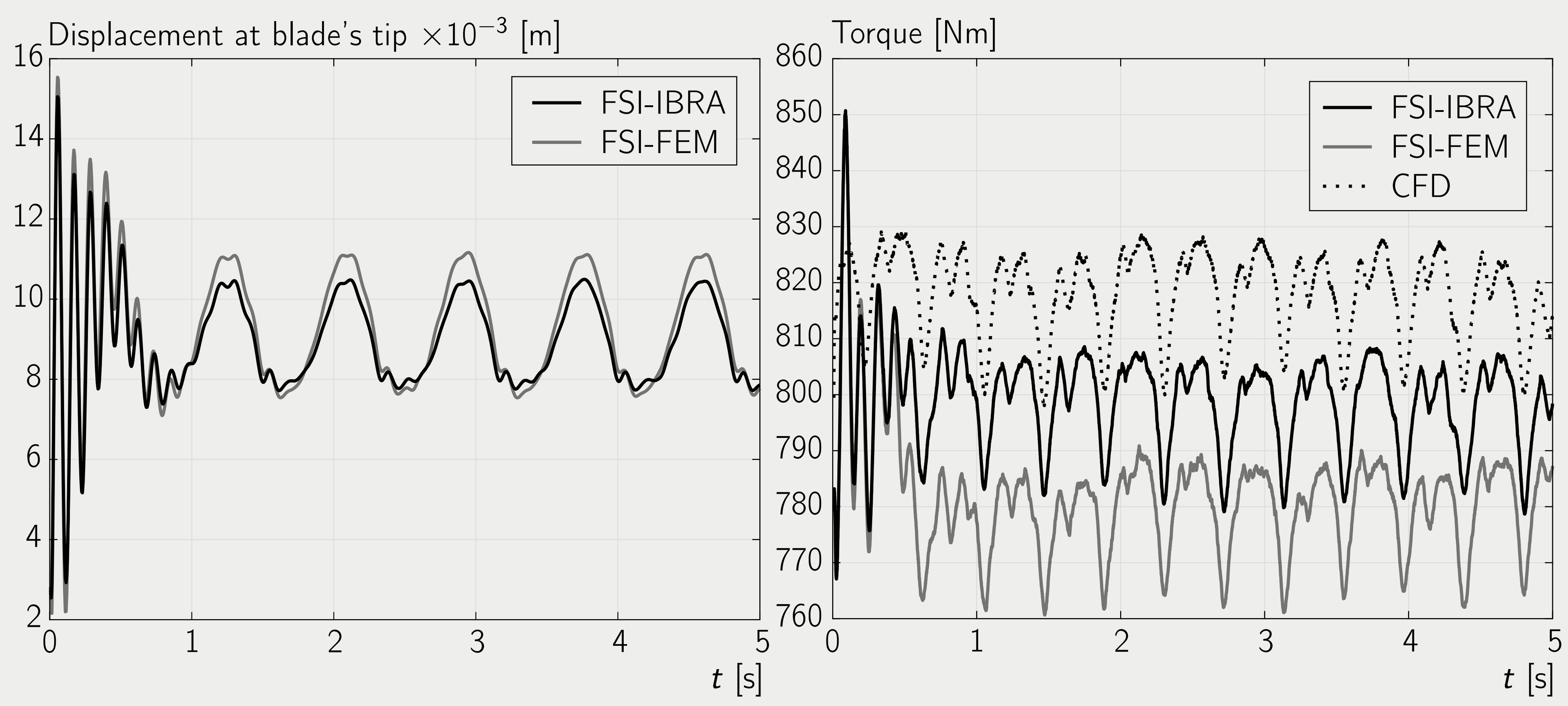
Eq. (2) can be inverted in case a field on $\mathscr{S}_{\mathrm{h}}$ is sought. In this way, displacement and traction fields can be exchanged between the fluid and the structural subdomains along their common interface. In practice, the low-order surface $\mathscr{S}_{\mathrm{h}}$ is projected onto the NURBS multipatch surface $\mathscr{S}$ for the evaluation of the integrals in Eq. 2, see Fig. 4(b).



(a) $t = 1.6$ s (FEM). (b) $t = 3$ s (FEM). (c) $t = 4.4$ s (FEM).

(d) $t = 1.6$ s (IBRA). (e) $t = 3$ s (IBRA). (f) $t = 4.4$ s (IBRA).

Figure 5: Q-criterion and blade deformation scaled by 170 at exemplary time instances for both FEM and IBRA computational models.



(a) Displacement at the tip of the right blade. (b) Total torque on both blades versus time.

Figure 6: Displacement at the tip of the right blade and total torque on both blades versus the simulation time.

Qualitatively, the isosurfaces of the Q-criterion in different time instances for the FSI simulations using both the FEM and the IBRA computational models is shown in the set of Figs. 5. For a quantitative comparison of the results, the time displacement curves of the right wind turbine blade and the total generated torque on the flexible blades is shown in the set of Figs. 6 demonstrating an excellent agreement of the results, thus extending IBRA of shell structures to FSI.

References

[1] Yavuz Başar and Wilfried B. Krätzig. *Mechanik der Flächentragwerke. Theorie, Berechnungsmethoden, Anwendungsbeispiele*. Braunschweig: Vieweg, 1985. ISBN: 978-3-322-93983-8.

[2] Thomas J. R. Hughes, J. Austin Cottrell, and Yuri Bazilevs. "Isogeometric analysis: CAD, finite elements, NURBS, exact geometry and mesh refinement". In: *Computer Methods in Applied Mechanics and Engineering* 194.39-41 (2005), pp. 4135–4195. ISSN: 00457825.

[3] Josef M. Kiendl, Kai-Uwe Bletzinger, Johannes Linhard, and Roland Wüchner. "Isogeometric shell analysis with Kirchhoff–Love elements". In: *Computer Methods in Applied Mechanics and Engineering* 198.49-52 (2009), pp. 3902–3914. ISSN: 00457825.

[4] D. Simms, S. Schreck, M. Hand, and L. J. Fingersh. "NREL unsteady aerodynamics experiment in the NASA-Ames wind tunnel: a comparison of predictions to measurements". In: *National Renewable Energy Laboratory Colorado, USA* (2001).

[5] M. Breitenberger, A. Apostolatos, B. Philipp, R. Wüchner, and K.-U. Bletzinger. "Analysis in computer aided design: Nonlinear isogeometric B-Rep analysis of shell structures". In: *Computer Methods in Applied Mechanics and Engineering* 284 (2015), pp. 401–457. ISSN: 00457825.

[6] Andreas Apostolatos, Robert Schmidt, Roland Wüchner, and Kai-Uwe Bletzinger. "A Nitsche-type formulation and comparison of the most common domain decomposition methods in isogeometric analysis". In: *International Journal for Numerical Methods in Engineering* 97.7 (2014), pp. 473–504. ISSN: 00295981.

[7] Andreas Apostolatos, Michael Breitenberger, Roland Wüchner, and Kai-Uwe Bletzinger. "Domain Decomposition Methods and Kirchhoff-Love Shell Multipatch Coupling in Isogeometric Analysis". In: *Isogeometric analysis and applications 2014*. Ed. by Bert Jüttler and Bernd Simeon. Vol. 107. Lecture Notes in Computational Science and Engineering. Cham, Heidelberg, and New York: Springer, 2015, pp. 73–101. ISBN: 978-3-319-23314-7.

[8] S. A. Sicklinger. "Stabilized Co-Simulation of Coupled Problems Including Fields and Signals". Dissertation. München, Germany: Chair of Structural Analysis, 2014. URL: https://mediatum.ub.tum.de/1223319.

[9] M. Breuer, G. de Nayer, M. Münsch, T. Gallinger, and R. Wüchner. "Fluid–structure interaction using a partitioned semi-implicit predictor–corrector coupling scheme for the application of large-eddy simulation". In: *Journal of Fluids and Structures* 29 (2012), pp. 107–130.