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Shape optimization of wind turbine blades in a fluid structure interaction simulation

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Micro Abstract
This contribution presents the shape optimization of wind turbine blades in the context of a fluid-structure interaction simulation.Vertex Morphing method,which is a node-based shape control technique, is used to find optimal design of the blades.Gradient-based optimization together with continuous adjoint based shape sensitivity analysis is employed to handle the large number of design variables.The fluid-structure interaction problem is solved using a partitioned, strong coupling algorithm.

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Introduction

There is a lot of studies in the literature focusing on the design and optimization of wind turbines. Different levels of fidelity ranging from low-fidelity to high-fidelity have been used as well as a wide range of different design variables, objective functions and constraints. Chehouri et al. [3] give a good Review of performance optimization techniques, objectives, design variables and constraints used in optimization of wind turbines. Traditionally, most of the wind turbine blade designs have been based on the low-fidelity models. In the recent years optimization of wind turbine blades using high-fidelity models has gained attention from the researchers and proves to be worthy. For example Dhert et al. [4] perform a shape optimization of wind turbine blades based on high-fidelity RANS CFD.
Upscaling is a trend in the new wind turbine designs which is mostly targeting the offshore wind sector. As the turbines grow in size and the structural components of the turbines become more flexible and light weight, taking into account the interaction of the fluid and the structure in the design and analysis of the wind turbines becomes increasingly more important. In recent times, several researchers have published the result of their research on fluid-structure interaction (FSI) simulation of wind turbines including [7] and [6].
The actual challenge is to further develop models and methods to deal with the high-fidelity FSI optimization of wind turbine blades. This allows to optimize the blades under the true loading conditions which introduce large blade deflections in the case of the flexible and large wind turbines. The present work takes a step towards that goal and presents high-fidelity aerodynamic shape optimization of wind turbine blades in an FSI simulation. A gradient-based shape optimization technique utilizing a continuous adjoint method is used to optimize the wind turbine blades. We use Vertex Morphing Technique, a node-based shape parametrization technique, to control the shape of the blades. In the following sections different building blocks of our simulation framework are introduced and finally some results from a test case are presented.

1 Vertex Morphing

Vertex Morphing Technique is a consistent approach for controlling the surface in the node-based shape optimization. The main idea behind it is to introduce a design control space $\mathbf{s}$ where the optimization problem is formulated together with a mapping operator $\mathbf{A}$ which relates the design control space $\mathbf{s}$ to the geometry space $\mathbf{x}$. After discretizing the geometry and the design control fields, the matrix operator $\mathbf{A}$ is formed and one can write:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{s} \tag{1}$$

In a shape optimization using the Vertex Morphing Technique, the matrix operator $\mathbf{A}$ is used twice. Once to map the design update in the design control space ($\Delta\mathbf{s}$) to the shape update in the geometry space ($\Delta\mathbf{x}$). This step is called forward mapping.

$$\Delta\mathbf{x} = \mathbf{A} \cdot \Delta\mathbf{s} \tag{2}$$

The transpose of the $\mathbf{A}$ matrix is used to map the surface sensitivities ($\frac{dJ}{d\mathbf{x}}$) to the design control space in order to calculate the gradient of the objective function with respect to the design variables (($\frac{dJ}{d\mathbf{s}}$) which is used for the gradient based optimization. This step is called backward mapping.

$$\frac{dJ}{d\mathbf{s}} = \frac{dJ}{d\mathbf{x}}\frac{d\mathbf{x}}{d\mathbf{s}} = \mathbf{A}^{\mathrm{T}} \cdot \frac{dJ}{d\mathbf{x}} \tag{3}$$

Equations 2 and 3 can be interpreted as smoothing operations, which together provide a means for arriving at smooth surface geometries throughout the optimization process even if the surface sensitivities are not smooth. For details and properties of the Vertex Morphing Technique, the interested reader is referred to [5] and [2].

2 Optimization and FSI framework

Figure 1 shows the schematic of the FSI optimization framework used in the current work. OpenFOAM® is used to solve the steady state Reynolds-averaged Navier-Stokes (RANS) flow around the blades, since performing large scale optimizations based on unsteady CFD is currently too costly. Therefore the unsteady effects such as the tower shadow effect are neglected. The in-house structural solver CARAT++ is used to solve for the deformations of the blades under the aerodynamic loads. The coupling and the communication between different blocks of the framework are realized through the coupling tool EMPIRE. The FSI problem is solved using a strong partitioned algorithm.
After the FSI loop has converged, the steady state continuous adjoint solver of Helyx® is used to calculate the sensitivity of the objective function with respect to the geometry parameters. The sensitivities from the adjoint solver are mapped from the geometry to the control space of the vertex morphing. Then the optimizer (steepest descent algorithm in this work) calculates the design updates in the control space. The mentioned design updates are then mapped from the control space to the geometry space using the Vertex Morphing's forward mapping. In the next step a new blade geometry is obtained, the mesh is updated and a new FSI loop starts.

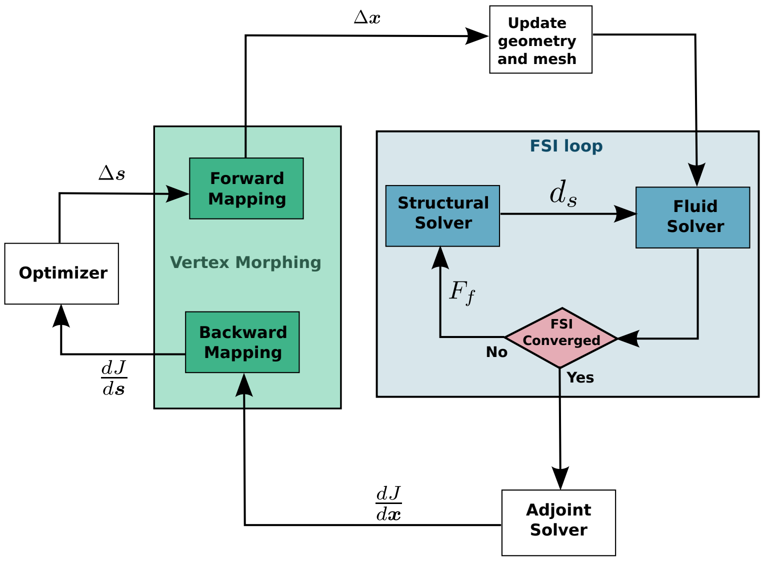

Figure 1. Schematic of the FSI optimization procedure.

3 Simulation and Results

As a test case, the aerodynamic shape optimization of the CX-100 HAWT in an FSI simulation is presented in this section. A steady state RANS simulation using Multi-Reference Frames (MRF) is used to simulate the effect of the rotating blades. The CFD mesh is made using the Pointwise mesh generation software [1]. The mesh consists of around 7.5 million hybrid (hexahedral and tetrahedral) cells. Figure 2 shows the CFD domain.

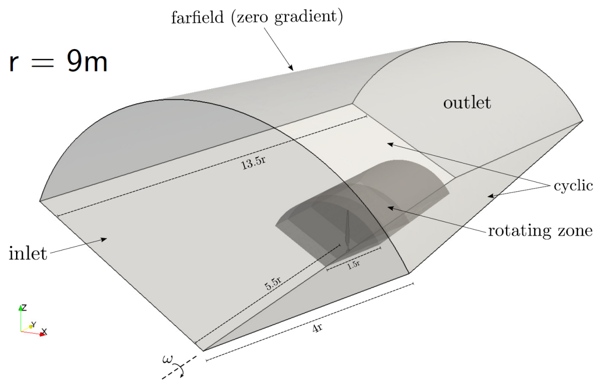

Figure 2. The CFD domain.

The structure of the blade is modeled using beam elements. This offers very fast calculations compared to the shell models but does not capture local surface deformations and stresses. However it offers enough accuracy for the aeroelastic shape optimization in FSI simulations. in order to transfer data between the surface of the blade and the beam elements a beam-surface mapper is used [8]. Figure 3 show the structural domain of the blade.

The objective function in the optimization process is maximizing the total generated power from a given constant wind velocity. The optimization process using the steepest descent algorithm runs for 14 iterations using a constant step size, before the mesh is distorted up to a point where the results are not accurate anymore. At the end of the optimization, the total generated power from the wind turbine is improved by 4.8%. Figure 4 shows the field of the shape update magnitude on both sides of the blade at the end of the optimization.

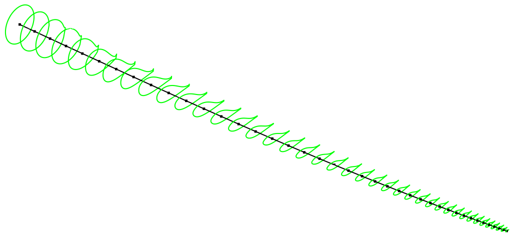

Figure 3. The structural model of the blade using beam elements.

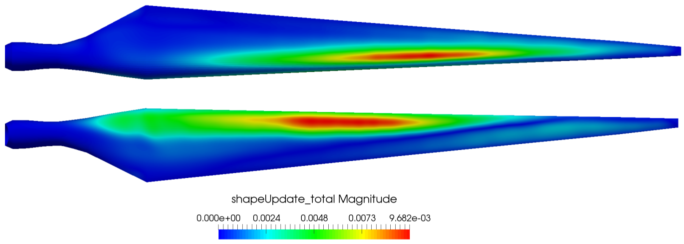

Figure 4. The field of shape update magnitude on both sides of the blade (m).

Conclusions

In this work, a framework for the FSI optimization of the wind turbine blades was successfully implemented and tested. The framework was used to optimize the total generated power from the CX-100 blades. In the future the framework will be extended and improved in order to include coupled adjoint solution and multidisciplinary multi-objective optimization of wind turbine blades under design constraints. Furthermore, the value of FSI optimization is more prominent when used on larger wind turbines. Therefore a logical next step is to carry out design optimization of a large offshore wind turbine e.g. the DTU 10-MW Reference Wind Turbine.

Acknowledgements

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