Fully Coupled Fluid-Structure Interaction Analysis of Wind Turbine Rotor Blades

Abaqus Technology Brief

Acknowledgement

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Summary

Wind turbines are used around the world as a source of renewable energy. While the operating principle of a wind turbine is simple, the detailed aerodynamic and mechanical behavior of the system is quite complex. Of particular interest to blade designers is the coupled interaction between the rotor aerodynamics and the response of the structure. Including this interaction effect in the design process will allow for a better prediction of the blade loading and deflection.

In this Technology Brief, a fully coupled fluid-structure interaction analysis of a wind turbine rotor is presented. Abaqus/Standard and STAR-CCM+ are directly coupled through the SIMULIA co-simulation engine. With this approach, a high fidelity modeling strategy can be used to develop an accurate understanding of the blade dynamics.

Background

It is well known that the airflow around a wind turbine blade induces a number of complex aerodynamic phenomena. As a result, accurate estimates of the blade service loads are not easily predicted. A number of design methods have evolved over the years, each using differing levels of simplification and approximation.

Computational fluid dynamics (CFD) is a powerful analytical technique and is a regularly used tool in the design of wind turbines. By directly coupling a CFD analysis to a structural finite element analysis, the strengths of both tools can be applied simultaneously, allowing designers to capture the real-time interaction of fluid and structural behavior.

The analysis presented here is based on a robust, seamless, easy-to-use fluid-structure interaction (FSI) solution using Abaqus and STAR-CCM+, where Abaqus/Standard is used for the structural simulation of the blade and STAR-CCM+ is used for the fluid simulation. The SIMULIA Co-Simulation Engine (CSE) allows the two programs to be directly coupled without third-party interface software. We will demonstrate one-way and fully coupled simulations.

In the one-way sequentially coupled simulation, the blade wind loads are first computed in STAR-CCM+. This is followed by an Abaqus/Standard static structural analysis. The results are then used to define and run a stable, fully coupled bi-directional analysis. The fully coupled analysis determines the nonlinear blade deformation behavior caused by stochastic variations of wind loads (arising from turbulence) that are in turn affected by blade deformation.

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Key Abaqus Features and Benefits

- Abaqus - STAR CCM+ direct coupling through the SIMULIA Co-Simulation Engine (CSE)
- One-way (unidirectional) and fully bi-directional scalable coupling solutions with Abaqus/Standard and Abaqus/Explicit
- Composite material modeling capabilities for accurate structural representation of wind turbine blades

Geometry and Model

In this study, the structural model of the blades (Figure 1) is created in Abaqus/CAE. A single blade is approximately 48m in length and modeled with 18,471 S4R composite shell elements. The blades are connected to a rigid hub with a kinematic coupling constraint.

The CFD model contains a rotating region in the immediate vicinity of the blades, and a fixed region far away from the blades. The two regions interact through a slid-

Figure 1: Wind turbine structural model geometry

ing boundary and the dynamic mesh capability in STAR-CCM+. Partitioning the CFD domain into two regions permits use of appropriate mesh densities for different regions of mechanics significance. The rotating region contains of 639,780 cells (circular disc-shaped region around the blades in Figure 2) and the stationary region is meshed with 58,700 cells. Both domains are discretized with a polyhedral mesh, which is a powerful capability in STAR-CCM+ that allows accurate solutions to be obtained in a relatively efficient manner.

Typical representative conditions are chosen: wind inflow velocity of 9 m/s and a blade tip speed of 60 m/s, yielding a blade tip speed ratio of 6.7 and a rotation rate of 12 RPM. The blades are assumed to be in steady-state rotation at the start of the analysis, and the tower and drive train effects are ignored. A fixed blade pitch angle is used, and constant magnitude wind loads are specified with a fixed angle of attack of 14°.

Analysis Approach

The complete three step workflow, building from individual Abaqus-only and CFD-only analyses to the definition of the fully coupled FSI analysis, is summarized in Figure 3.

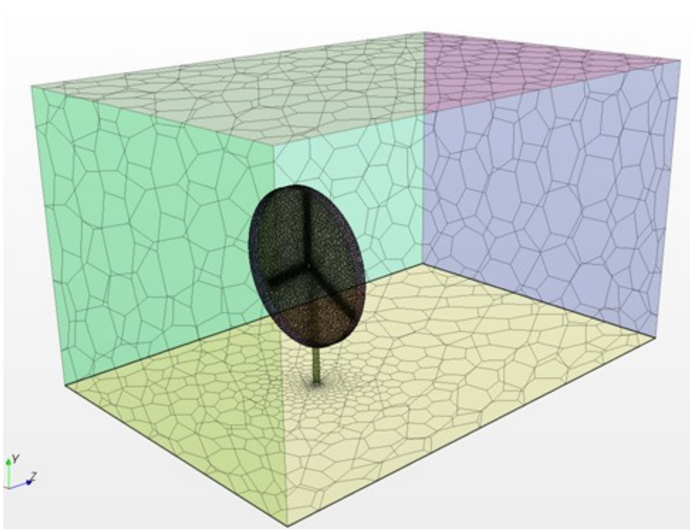

Figure 2: CFD mesh representation

It is important to ensure the stability of both the structural and CFD simulations in a fully coupled FSI analysis. To this end, it is advantageous to understand the dynamic characteristics of the structural model and then tune the FSI analysis attributes to ensure overall analysis stability.

In the first step of the workflow, the dynamic characteristics of the blades were studied in Abaqus/Standard and a first natural bending frequency of 0.962 Hz was obtained for the structural model alone. Based on this result and a blade rotation period of 5 seconds (12 RPM), the flow and blade speed assumptions were likely to yield a stable model.

The first step was completed by performing a CFD analysis that used a rigid blade assumption; the STAR-CCM+ 6-DOF solver was used for this purpose. The 6-DOF analysis provided useful information about appropriate mesh morpher settings used in the fully coupled co-simulation.

The second step further prepared for the fully coupled simulation by performing a Moving Reference Frame (MRF) analysis in STAR-CCM+, again with rigid blades. This determined the fluid steady state corresponding to a blade rotation speed of 12 RPM. To develop some comparative results, a one-way sequential FSI analysis was then conducted by exporting the wind pressure obtained from the MRF analysis to serve as loading in an Abaqus/Standard static analysis.

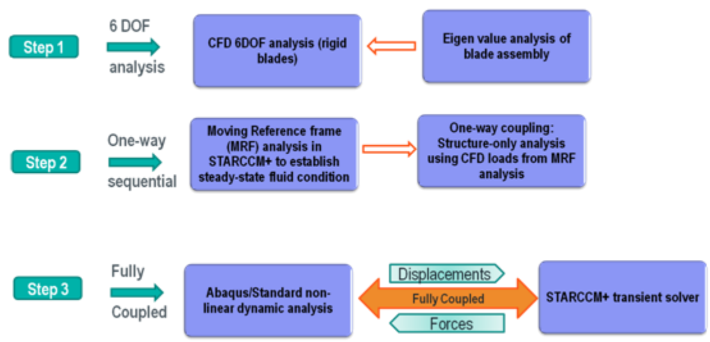

Figure 3: Three-step simulation workflow

A fully coupled bi-directional FSI analysis was then performed in the third step using the fluid state determined in the second step as the initial condition. A constant coupling step size of 0.05s was chosen to capture all essential dynamic behavior caused by blade bending and vibration. Pressure and wall shear stress fields were exported from STAR-CCM+ while nodal displacements were exported from the Abaqus structure model. The outer surface of the blade geometry defined the coupling interface for the two models.

For all CFD analyses, a segregated flow model with k-ω turbulence was used. For both the bi-directional FSI and 6-DOF analyses, the STAR-CCM+ implicit unsteady solver is used to advance the solution in time; the MRF solution is steady state. The Abaqus/Standard implicit dynamic solution procedure was used for the bi-directional FSI analysis.

Results and Discussion

One-way Sequential Coupling

The steady state pressure field obtained from the STAR-CCM+ MRF analysis was used to load the blade in a static Abaqus analysis. This provided qualitative insight into the structural behavior of the blades, such as the location of peak stresses and the magnitude of bending deflection (Figures 4 and 5).

Bi-directional Coupling

A fully coupled bi-directional FSI analysis allows more accurate assessments of the blade stresses and dynamic displacement. Peak stresses and their locations on the blade in the bi-directionally coupled analysis are shown in Figure 6. A dynamic analysis yields higher magnitudes of stress compared to the one-way sequential static analysis. Figure 7 shows the oscillatory displacement of a blade tip through a single rotation, a dynamic behavior that can be studied only in fully coupled FSI analysis. Peak pressure distribution in the wake region for the deformable blade is on average 10% higher than that of a rigid blade. Figure 8 shows the contours of pressure and velocity magnitude in the air.

Figure 9 compares the torque at the turbine hub for the CFD-only 6-DOF and fully coupled FSI analyses. Note that the inclusion of blade flexibility and fluid-structure interaction modifies the time history and magnitude of the torque. The curves indicate that the initially chosen wind speed and rotation rate conditions are not fully compatible with a steady state condition. However, the physics captured by the fully coupled FSI solution will allow the steady state condition to emerge naturally as the simulation progresses.

Consistent with the higher torque, the out-of-plane force distribution along the leading edge of the deformable blade in a fully coupled FSI analysis is higher, on average, when compared to that of the rigid blades, as shown in Figure 10.

Summary

For the analysis of wind turbine blades, this Technology Brief has demonstrated the advantages of the fully coupled Abaqus-STARCCM+ co-simulation technique. When

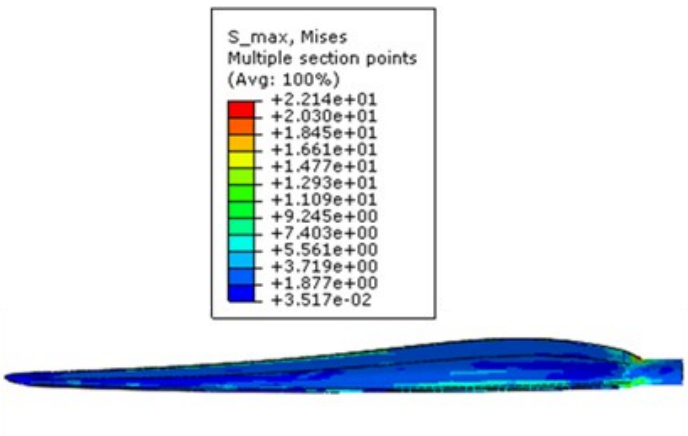

Figure 4: Mises stress (MPa), sequentially coupled FSI analysis

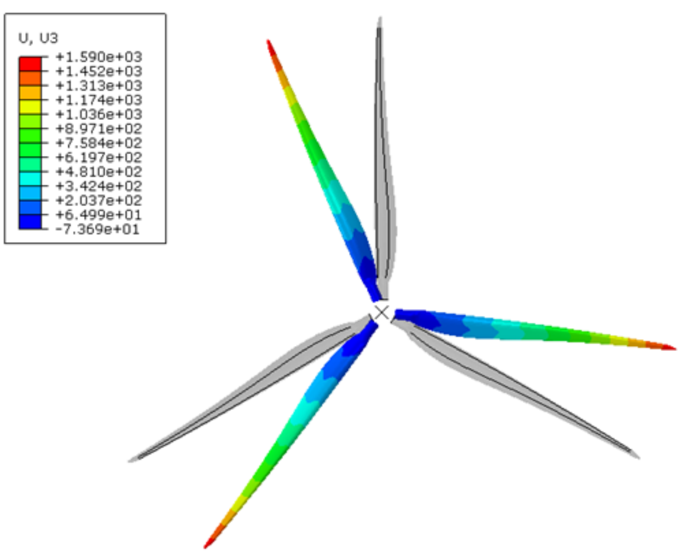

Figure 5: Bending deflection (mm), sequentially coupled FSI analysis

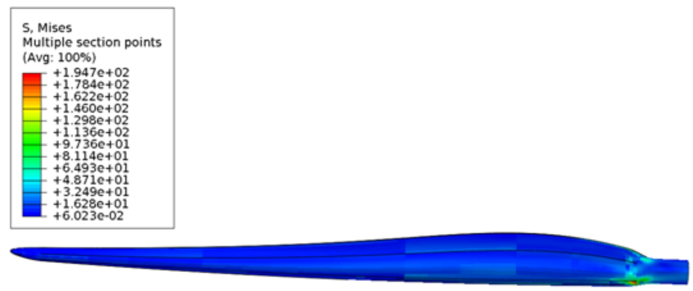

Figure 6: Peak Mises stress (MPa), fully coupled FSI analysis

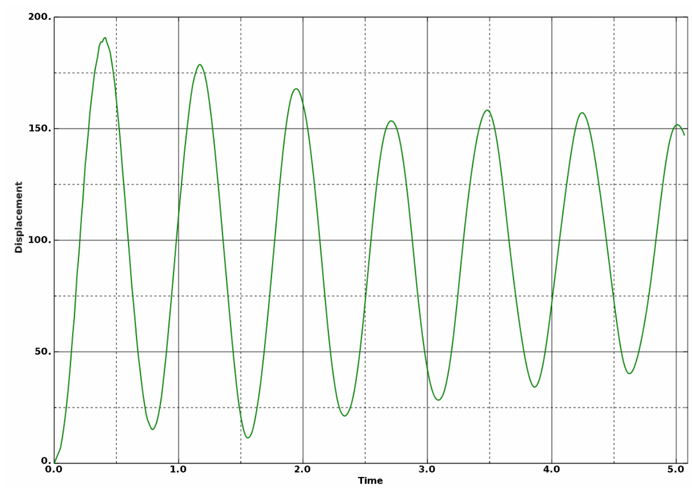

Figure 7: Blade tip displacement through one full rotor revolution, fully coupled FSI analysis

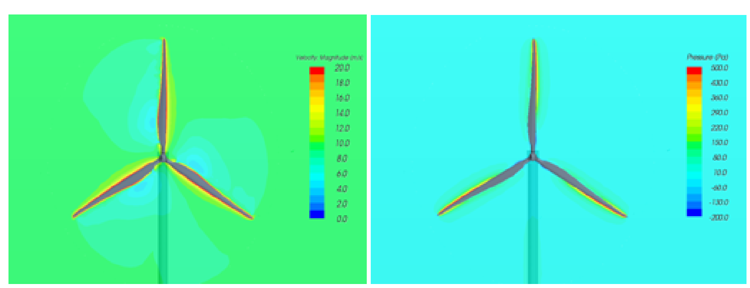

Figure 8: Velocity and pressure contours, fully coupled FSI analysis

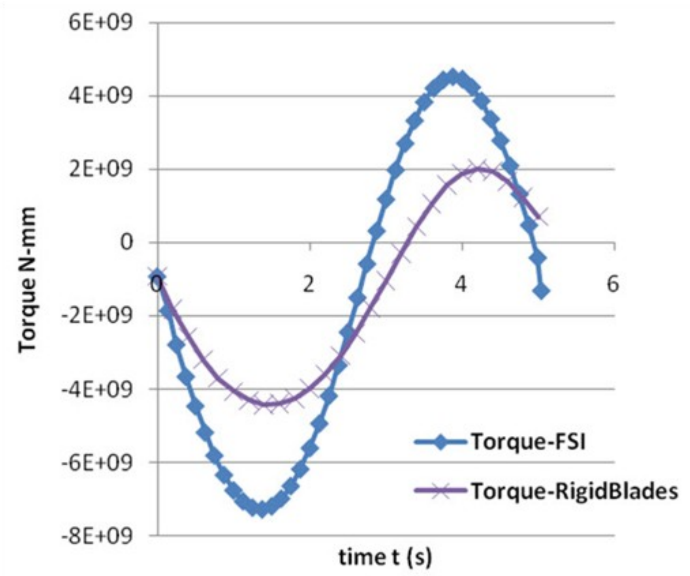

Figure 9: Torque output comparison between fully coupled FSI and CFD-only analyses

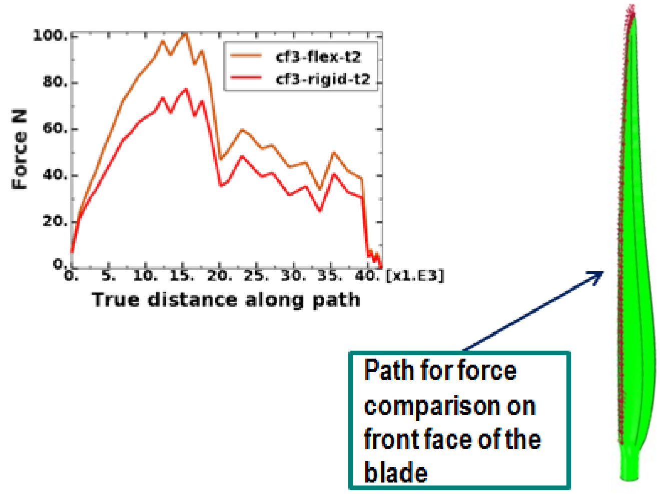

Figure 10: Representative force distribution on the blade leading edge: comparison of rigid and elastic blade models

compared to CFD-only analyses, more physically meaningful simulations are permitted by the inclusion of structural flexibility and true fluid-structure interaction.

The improved fidelity of fluid pressure and velocity distribution in the vicinity of the blades allows designers to better understand the turbine operating conditions as well as tune blade pitch angles during simulation to optimize turbine output. This simulation approach provides the necessary analysis framework to investigate blade stresses and displacement histories and can be extended to include other components of the turbine system.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus 6.12 documentation references:

- 'Co-simulation,' Section 17.1 of the Abaqus Analysis User's Manual

References

– STAR-CCM+ 6.02 User's Guide 6.02
– Hartwanger, David and Dr. Andrej Horvat, *3D Modeling of a wind turbine using CFD*, 2008 NAFEMS Conference

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