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Numerical Fluid-Structure Interaction Study on the NREL 5MW HAWT

Amr M Halawa[1], Matias Sessarego[2], Wen Z Shen[2] and Shigeo Yoshida[3]

[1] Department of Earth System Science and Technology, Kyushu University, Kasuga, Fukuoka, Japan
[2] Department of Wind Energy, Technical University of Denmark, 2800 Kongens Lyngby, Denmark
[3] Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, Japan

E-mail: `amrhalawa@riam.kyushu-u.ac.jp`

Abstract. The development of reliable Fluid-Structure Interaction (FSI) simulation tools and models for the wind turbines is a critical step in the design procedure towards achieving optimized large wind turbine structures. Such approach will mitigate the aeroelastic instabilities like: torsional flutter, stall flutter and edgewise instability that introduce extra stresses to the turbine structure leading to reduced life time and substantial failures. In this study, FSI simulations were held using the commercial package Ansys v18.2 solvers as a preliminary step towards our on-going development of a reliable Open-Source solver. These simulations were applied to the full-scale rotor blades of the NREL 5MW reference horizontal axis wind turbine. The aerodynamic loads and structural responses computations were carried out using a steady-state FSI analysis. The computations were run on the Kyushu University multi-core Linux cluster using the public domain openMPI implementation of the standard message passing interface (MPI). Finally, the results were validated against the Technical University of Denmark's (DTU) MIRAS aeroelastic code results as well as the widely used FLEX5-Q^{3}UIC and FAST codes in different cases showing reasonable agreement.

1. Introduction

The increased potential for the extraction of wind energy has led to a considerable development in the wind turbines designs. The turbine blades are getting larger and thus introducing new load effects. The flexibility of large wind turbines yields an interaction between the fluid flow and the internal structure loading causing what is known as Fluid-Structure Interaction (FSI) or aeroelastic effects. The consequences of these effects are many instability problems like torsional flutter, stall flutter and edgewise instability imposing extra stresses on the blade structure through fatigue loads that potentially end up to wind turbine failures. Hence, developing reliable FSI simulation tools and models for the blades of wind turbines is a critical step towards developing and optimizing the large wind turbines designs. Many recent studies are centered around the FSI development. Hsu and Bazilevs [1] simulated a full scale turbine using a fully coupled 3D FSI approach by a low order FEM-based ALE-VMS technique. Rafiee et al. [2] investigated the aeroelastic behavior using modified BEM and CFD then constructed an iterative FSI approach. Wang et al. [3] established an FSI model using CFD and FEA with one-way coupling interface between them. Carrión et al. [4] applied a CFD-CSD method to perform aeroelastic

analysis on NREL and MEXICO wind turbines where flapwise and edgewise instabilities were studied. Recently, Heinz et al. [5] conducted a high-fedility study on the blade of the reference wind turbine DTU 10 MW to investigate the aeroelastic response in deep stall conditions using HAWC2CFD tool [6]. Dose et al. [7] coupled OpenFOAM to an in-house structural beam solver to investigate the aeroelasticity of the NREL 5MW wind turbine blade at high wind speeds.

In the current work, as a preliminary step towards our on-going development of a reliable Open-Source solver, FSI simulations were held using the commercial package Ansys v18.2. An incompressible coupled pressure-based solver was used in Ansys Fluent to compute the aerodynamic loading on the rotor blades. Then, the pressure loads were passed on to Ansys Mechanical to calculate the induced stresses and deformations of the blade. This solver was applied to the full-scale rotor blades of the NREL 5MW reference horizontal axis wind turbine (HAWT) [10] shown in Figure 1. Furthermore, a dynamic mesh was used to consider the deformations and displacements in the FSI interface. The computations were run on the Kyushu University multi-core Linux cluster server using the public domain openMPI implementation of the standard message passing interface (MPI). Afterwards, the solver results were validated against the Technical University of Denmark's (DTU) MIRAS-FLEX [11] aeroelastic code results as well as the widely used FLEX5-Q^{3}UIC [12] and FAST [13] codes in different cases.

Figure 1: The NREL 5 MW wind turbine blade [10].

2. Methodology

In this section, a steady-state 1-way FSI analysis was performed to get the aeroelastic response due to the aerodynamic loading on NREL 5MW reference HAWT blade. The blade characteristic geometry data was based on previous literature data from Bazilevs et al. [10] and Sessarego et al. [11]. Firstly, the pressure loads on the blade surface were computed using Ansys Fluent then passed on to Ansys Mechanical to compute the stresses and deformations on the blade. The blade had a length of 63 m and a pitch angle at the tip of 0 degrees. Due to the symmetry of the turbine rotor, shown in Figure 2a and to save the computational cost and time, a single blade only was considered for this simulation with periodic/cyclic boundary conditions to account for the other two blades similarity in a rotational manner.

In order to apply the CFD solver to the problem, a sizable fluid domain needed to be defined around the blade extending far enough upstream and downstream. Afterwards, that domain needed to be discretized reasonably to capture the physical properties of the flow around the turbine as well as the mutual interaction with the surfaces. Consequently, a large domain was constructed around the blade as shown in Figure 2b accounting for the downstream wake shedding. A domain sensitivity study was done using various meshes from coarse to fine ones with different number of elements to guarantee mesh-independent solutions. Finally, the chosen domain and mesh specifications are shown in detail as follows.
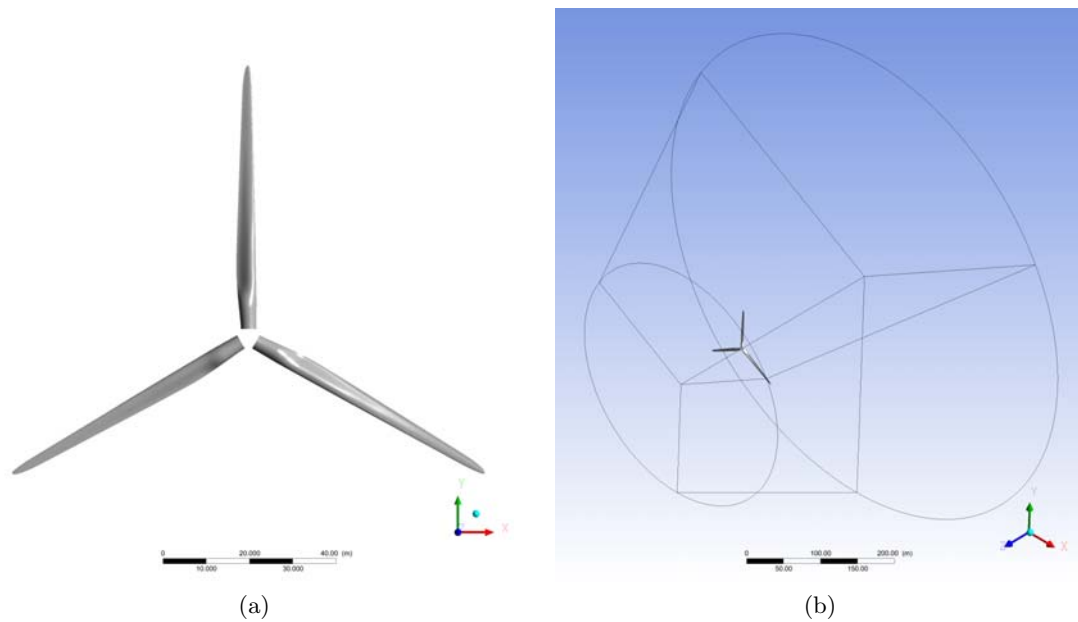
Figure 2: (a) The NREL 5 MW wind turbine rotor [10]. (b) The mesh domain boundaries around the NREL 5 MW HAWT rotor.

A dense unstructured mesh was constructed around that blade with $14,958,918$ hybrid cells and $3,962,585$ nodes with clustered density around the blade region as shown in Figure 3a. A special refined structured layers were generated near the blade surface to capture the boundary layer properties and viscous effects as shown in Figure 3b.
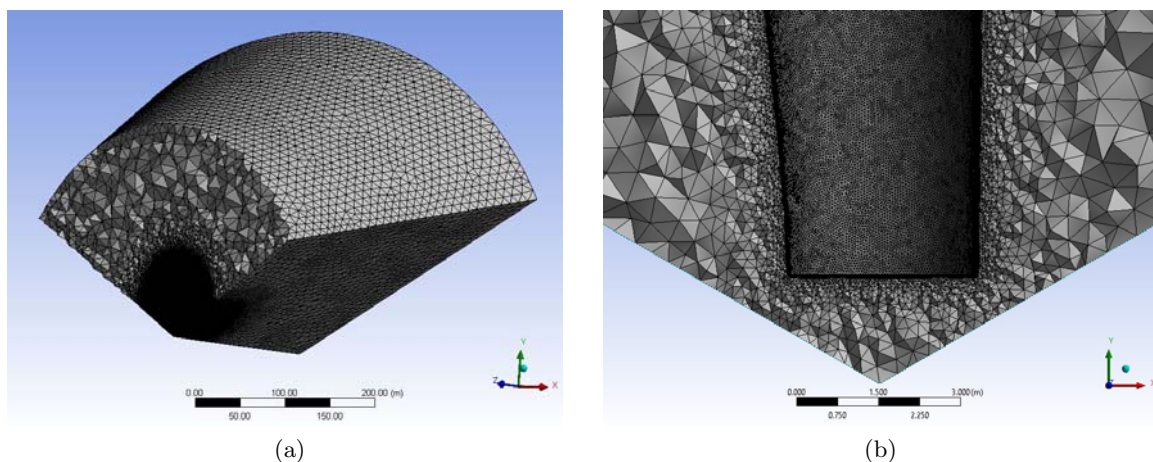

Figure 3: The constructed fluid mesh around the NREL 5 MW HAWT blade. (a) A sectional view of the whole mesh. (b) A close-up view on the refined mesh near the blade surface.

The mesh quality was checked to ensure the accuracy of the solution. The average orthogonality quality was found to be 0.79128 with a standard deviation of 0.11992 as shown in Figure 4, which is very reasonable. Moreover, the mesh skewness quality was found to be 0.20763 with a standard deviation of 0.12074 as shown in Figure 5, which is very acceptable too.
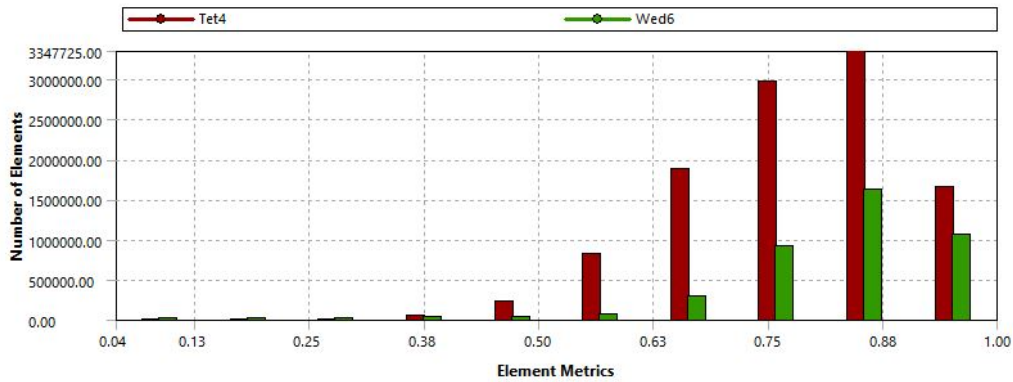
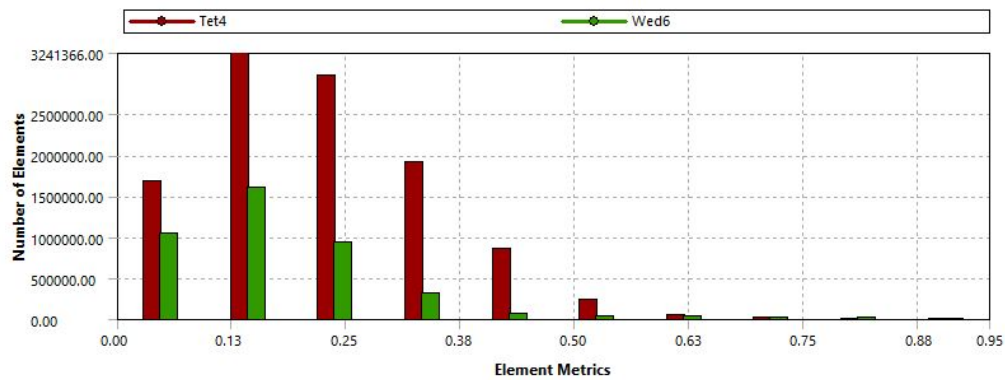Figure 4: Orthogonality quality of the constructed fluid mesh.

Figure 5: Skewness quality of the constructed fluid mesh.

In preparation for the structural part of the solver, a reasonable surface mesh is required for the blade before proceeding to the finite element analysis. Figure 6 depicts the constructed mesh on the NREL 5 MW blade surface. The mesh is structured with 5, 635 elements and 5, 639 nodes. Besides, to guarantee enough accuracy of the solution, the mesh metrics were calculated and shown as follows. Figures 7 and 8 shows the orthogonality and skewness quality of the constructed structural mesh, respectively. It's obvious that both of them show very acceptable metrics to achieve solutions with good enough accuracy.
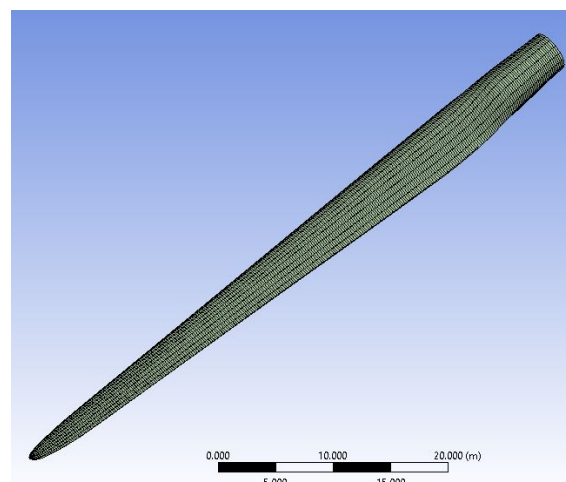

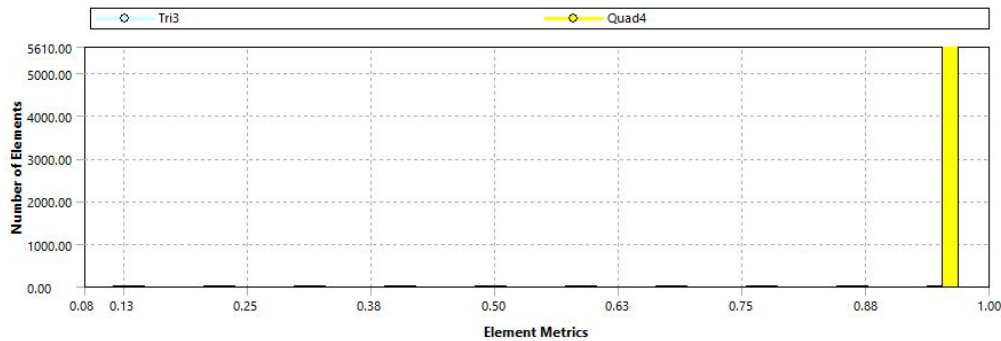Figure 6: The constructed structural mesh on the NREL 5 MW HAWT blade.

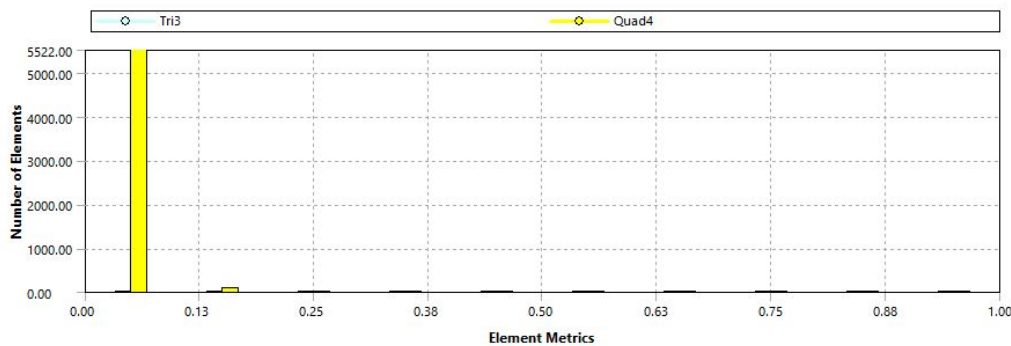Figure 7:   Orthogonality quality of the constructed structural mesh.

Figure 8:   Skewness quality of the constructed structural mesh.

3. Results and Discussions

In this section, the results of the test cases will be shown and validated against DTU's MIRAS-FLEX results as well as FLEX5-Q^{3}UIC and FAST codes [11]. DTU's MIRAS-FLEX is a coupled aeroelastic code that is based on a three-dimensional viscous–inviscid method for wind turbine computations. The case study for this work is based on the test case #2 of Sessarego et al. [11]. The inflow is steady and uniform wind tested at speeds of 10 m/s and 14 m/s. The tip speed ratio (TSR) is fixed at 7.55 up to the maximum rotor angular speed 12.1 rpm at 10 m/s. For the 14 m/s wind speed, the rotor angular speed is fixed at 12.1 rpm allowing for a decrease in the tip-speed ratio with the increased wind speed. For this specific case, the blade pitch angle is specified at a value of zero and fixed for all wind speeds. The pitch regulations had been discarded at the rated power, since it was more interesting to observe the stall behavior of MIRAS-FLEX and its comparison to FLEX5 and FAST as explained in detail by Matias et al [11]. Furthermore, zero values were assigned to the tower shadow, tilt angle and gravity to achieve non-oscillating loads [11]. The solver is applied using k-ω SST model to account for the turbulence effects. Moreover, the computations were run on the Kyushu University multi-core Linux cluster using the public domain openMPI implementation of the standard message passing interface (MPI).

In order to check the output power of this rotor, the generated torque by the rotor was firstly calculated and then multiplied by the rotational speed of the rotor. For the first case of 10 m/s wind speed and 11.4 RPM, the rotor torque was found to be 3221.85 $kN.m$ which matches well the FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX codes values which are roughly clustered around 3200 $kN.m$. Similarly, for the second case of 14 m/s wind speed and 12.1 RPM, the rotor torque was found to be 5725.74 $kN.m$ which is very comparable to those of FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX codes. Figures 9a and 9b shows the comparison between the current simulation

and the other codes for the aerodynamic power and thrust, respectively. The results generally agree well from all codes. However, the slight differences were due to the fact that some of the used airfoil data are based on two-dimensional polar measurements [14] as in FAST and FLEX5 while they are based on Q^3UIC simulations in MIRAS-FLEX.
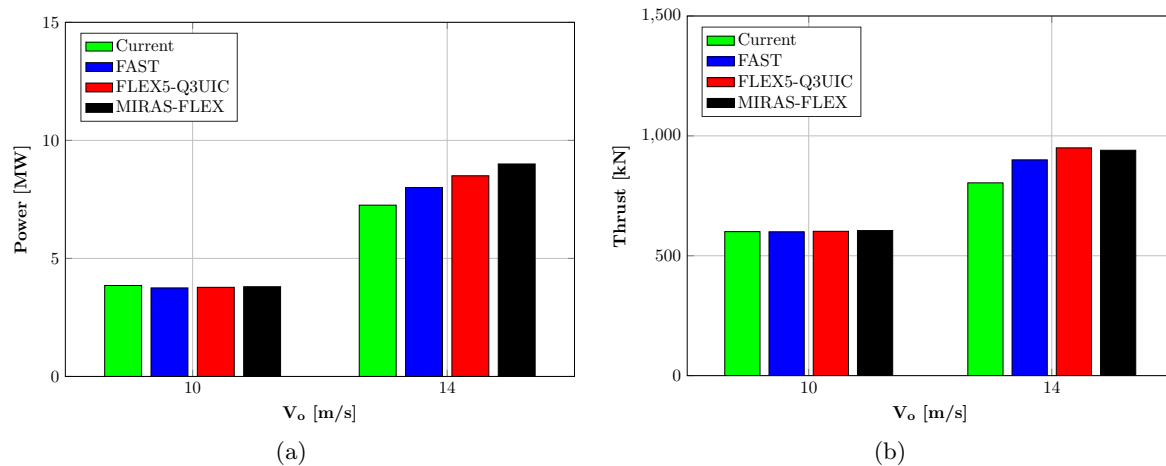

Figure 9: Aerodynamic Power (a) and Thrust (b) versus wind speed, V_o , for comparison between the current simulation, FAST, FLEX5-Q^3UIC, and MIRAS-FLEX.

On the other hand, the loading distribution on the blade in the span-wise direction was achieved by applying two cutting planes to two span-wise stations $r/R = 0.4$ and $r/R = 0.8$ as shown in Figure 10. The extracted aerodynamic loads which are normal and tangential to the turbine's rotor plane are depicted in Figures 11 and 12, respectively for increasing wind speeds and rotor RPM. The current simulation results agree well with the results from FAST, FLEX5-Q^3UIC, and MIRAS-FLEX. The values are quite identical at the first case study at a wind speed of 10 m/s since it's closer to the rated speed. However, for the second case of 14 m/s speed, the values are slightly varying due to the high loads affecting the rotor blades at high speeds. Such high loads yield considerable deflections as will be shown later in the structural results which in turn induce flow instabilities.
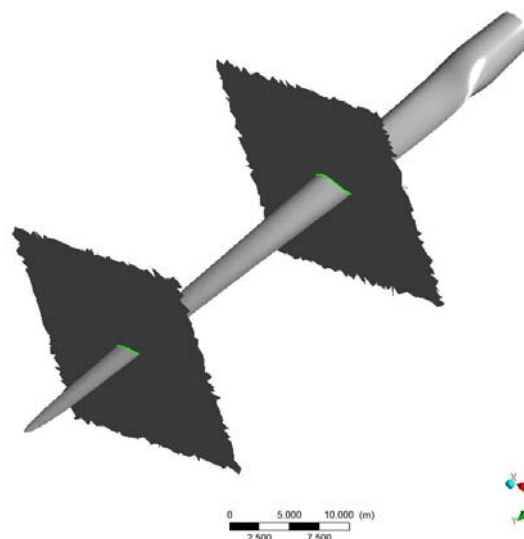

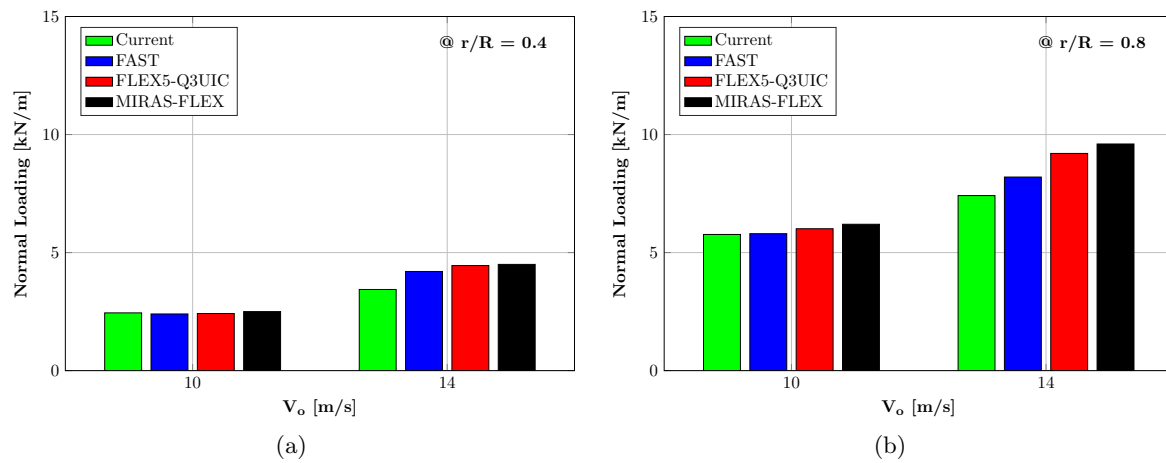Figure 10: The span-wise locations of the cutting planes on the blade.

Figure 11: Normal loads to the rotor plane comparison between the current simulation, FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX for increasing wind speeds and rotor RPM at two span-wise locations: (a) $r/R = 0.4$. (b) $r/R = 0.8$.
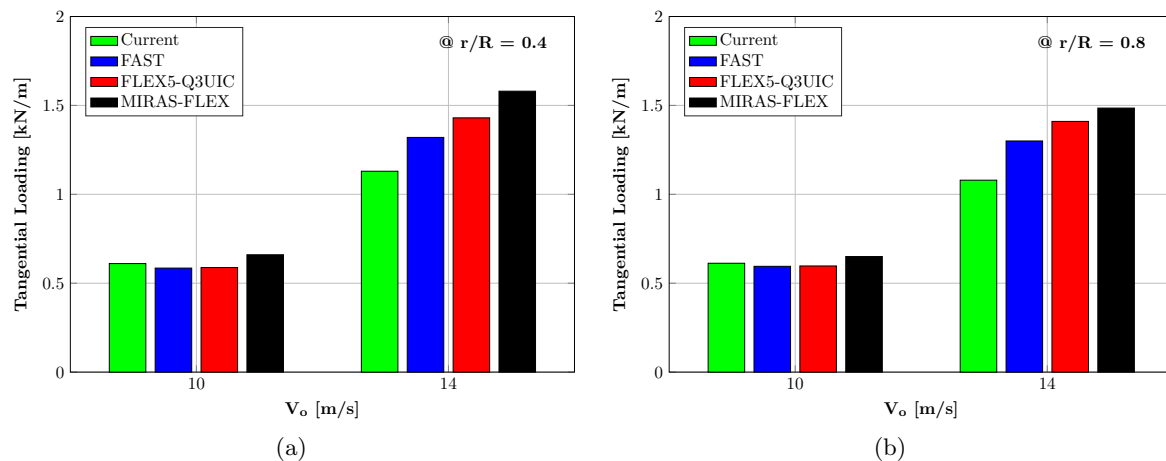

Figure 12: Tangential loads to the rotor plane comparison between the current simulation, FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX for increasing wind speeds and rotor RPM at two span-wise locations: (a) $r/R = 0.4$. (b) $r/R = 0.8$.

Figures 13a and 13b show the corresponding aeroelastic out-of-plane deflections of the rotor blades for the cases of wind speeds of 10 m/s and 14 m/s, respectively. It's obvious that at higher wind speed the deflection of the blade is larger and consequently inducing more stresses. To validate the results, the resultant tip deflections in both cases were compared against FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX codes as shown in Figure 14. The current simulation values are in good agreement with the other codes values. The results might be slightly higher in the second case of 14 m/s wind speed due to the accumulated slight errors from the aerodynamic par. Besides, an approximated estimate for the structural properties of the blade that were based on the NREL's technical report [15] and Cornell's data [16] was used in the structural part. Such an approximation was necessary to fit the model specifications in the current simulation, though it's acceptable since it yielded reasonable fluid-structure interaction results.
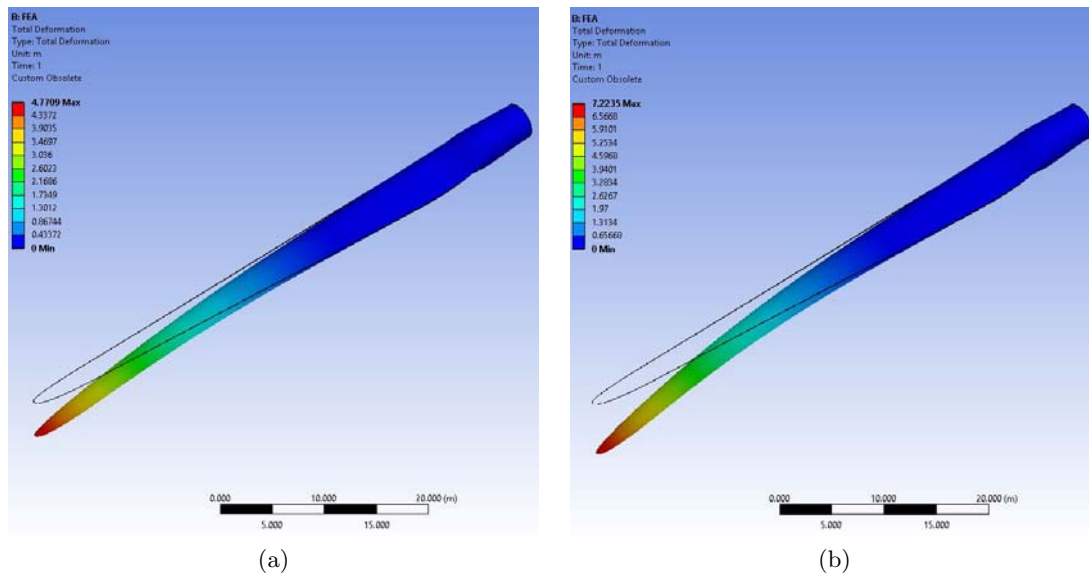
Figure 13: Aeroelastic deformation of the NREL 5MW HAWT blade at two speeds: (a) $V_o = 10\ m/s$. (b) $V_o = 14\ m/s$.
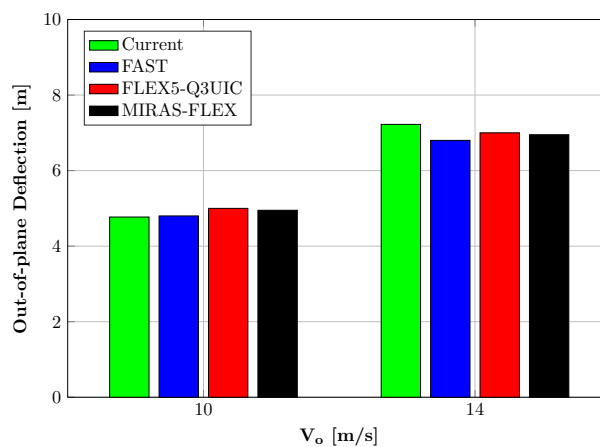

Figure 14: Out-of-plane blade tip deflections comparison between the current simulation, FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX for increasing wind speeds and rotor RPM.

4. Conclusions and Future Work

In the current work, FSI simulations were held on the full-scale rotor blades of the NREL 5MW reference horizontal axis wind turbine (HAWT) and validated against the famous FSI codes; FAST, FLEX5-Q^{3}UIC, and MIRAS-FLEX. The results from all codes were generally in a very good agreement for both the aerodynamic and structural parts. The results match well near the rated wind speed while slightly vary beyond it due to the inherent instabilities associated with higher wind speeds that needs further study. Besides, the current simulations shows a good prediction for the FSI behavior of the NREL 5MW HAWT rotor which will help developing more complicated solvers in the future. One aspect to account for in the coming work, is to perform FSI analysis using more complex inlet flow conditions to aid in studying the different instabilities in the flow. Besides, the FSI technique should be upgraded to the more realistic

transient 2-way approach to achieve better accuracy and prediction of the turbine behavior and response to the various flow stimulants. Last but not the least, further simulations on the NREL 5MW turbine model are being carried out on another in-house developed Open-Source solver and will be published soon.

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