CFD Methodology for Wind Turbines Fluid-Structure Interaction

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1. Motivations

The design trend in the up-scaling of the rotor diameter of Horizontal Axis Wind Turbines (HAWTs) implies more flexible blades that significantly deform under the aerodynamic loading. Industry standards for HAWTs aeroelastic simulations are based on Blade Element Momentum Theory offering a good computational efficiency and an acceptable flow response, thanks to additional sub-models. However, the accuracy of this approach is limited when dealing with large HAWT rotors, due to the existence of highly skewed flows, heavy detachments and important elastic blade deflections. Hence, the use of more sophisticated Computational Fluid Dynamics (CFD) techniques coupled with Computation Solid Dynamics (CSM) to accurately handle Fluid-Structure Interactions (FSI) is justified.

2. Objectives

The research tackles two major issues concerning efficient FSI simulations of HAWTs. One for the development of a flow mesh deformation technology achieving a good trade-off between mesh quality, scalability, robustness and computational cost for 3D meshes accounting multi-million points. Another for the extension of a frequency domain methodology to solve, in a cost effective way, the URANS and solid dynamics equations, namely the NonLinear Harmonic method (NLH), to handle the 2-way coupling between a fluid in motion and a deformable elastic structure for steady and periodic unsteady aeroelastic interaction.

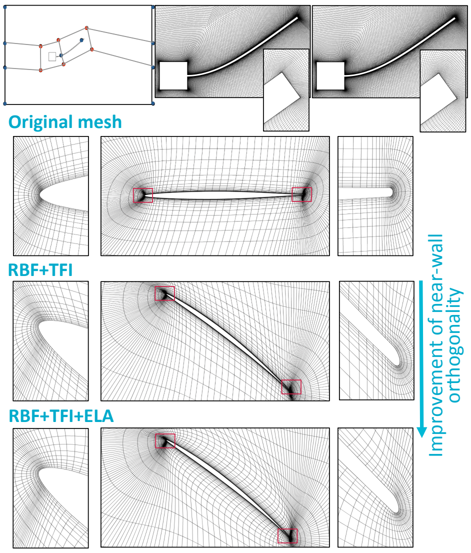
3. Methods

The methodology, the numerical aeroelastic developments and the simulations were performed within the CFD package FINE^{TM}/Turbo based on an Finite Volume Method on multi-block structured flow meshes (see NUMECA Int., 2013).

3.1 Hybrid flow mesh deformation approach

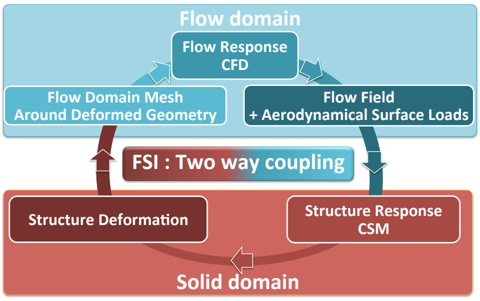
HAWTs accounts structural displacements inside 3D multimillion flow cells meshes that need to be readapted to structural deformations. For multi-block structured viscous mesh deformations, a new efficient hybrid approach based on the combination Radial Basis Function (RBF) for topological mesh node deformations, TransFinite Interpolation (TFI) for 3D multi-block mesh reconstructions and Elastic Analogy (ELA) for 3D mesh optimizations has been implemented. ELA equations are solved with a multigrid and parallelized solver, assuming a heterogeneous distribution of fictitious Young modulus.

For unsteady FSI simulations using the NLH methodology, the unsteady mesh node motion is mapped in frequency domain. This is achieved by independently applying the mesh deformation to time-averaged and harmonic displacements.

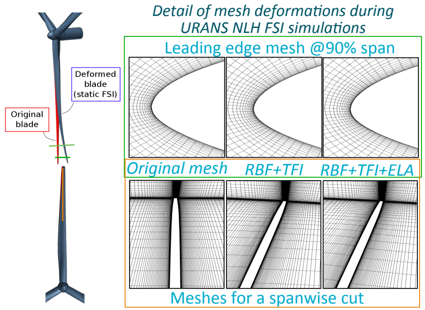


3.2 FSI 2-way coupling methodology

The level of complexity of the used technologies for the flow modeling is increased together with the interaction of the multi-physical processes involved. The FSI methodology is based on a strong 2-way coupling between CFD and CSM.


Flow domain
Flow Response CFD
Flow Domain Mesh Around Deformed Geometry
Flow Field + Aerodynamical Surface Loads
FSI : Two way coupling
Structure Deformation
Structure Response CSM
Solid domain

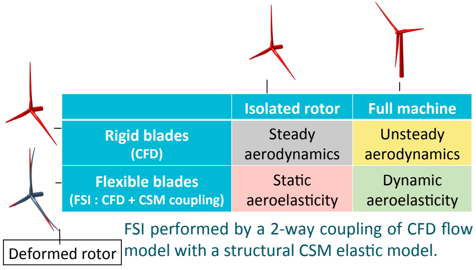
Hybrid mesh deformation on a 3D HAWTs mesh (7 10^6nodes)



Detail of mesh deformations during URANS NLH FSI simulations
Leading edge mesh @90% span
Original mesh *RBF+TFI* *RBF+TFI+ELA*
Meshes for a spanwise cut

CPU time for different mesh deformation methods			
Laplacian smoothing	RBF[1] [1]Estimated based on the mesh size	RBF+TFI	RBF+TFI+ELA
Fails	~267 days	2’ 48”	6 h 14’

Data corresponds for a 1 proc @2.6 GHz



	Isolated rotor	Full machine
Rigid blades (CFD)	Steady aerodynamics	Unsteady aerodynamics
Flexible blades (FSI : CFD + CSM coupling)	Static aeroelasticity	Dynamic aeroelasticity

FSI performed by a 2-way coupling of CFD flow model with a structural CSM elastic model.

3.2.1 Steady CFD flow model

A Reynolds Averaged Navier Stokes (RANS) approach is used to perform 3D steady simulations. By the interesting trade-off between accuracy and computational time of RANS, it has become the industry standard for CFD analysis.

3.2.2 Unsteady CFD flow model

Regarding unsteady flow simulations, industry relies on URANS. However, the large time needed for simulations on complex geometries by solving URANS in the time domain with a time integration is often incompatible with industrial workflows.

A less costly alternative, the possibility of the application of the NLH methodology was explored in this research. Indeed, the NLH approach presented by Vilmin et al. (2006), allows to drastically reduce the required computational time by assuming that the unsteady nature of the flow is periodic and writing the URANS equations in the frequency domain.

The NLH equations are only space-dependent and efficiently solved via pseudo-time integration. In turbomachinery and HAWTs fields, only a single blade passage need to be meshed.

Time mean + Sum of periodic perturbations:

$$U(\vec{x},t)=\bar{U}(\vec{x})+\sum_n U''_n(\vec{x},t)$$

Fourier decomposition of periodic perturbations:

$$U''_n(\vec{x},t)=\sum_{h=1}^{N_h}\left[\tilde{U}\Big|_h(\vec{x})e^{I\omega_h t}+\tilde{U}\Big|_{-h}(\vec{x})e^{-I\omega_h t}\right]$$

NLH equations:

Pseudo-time derivative, Frequency source, Convective fluxes, Viscous fluxes, Sources

Time-mean:
$$\boxed{\frac{\partial\bar{U}}{\partial\chi}\Omega}+\sum_{\text{Cell faces}}\left(\boxed{\bar{\vec{F}}_C}-\boxed{\bar{\vec{F}}_V}\right)\bullet\vec{S}=\boxed{\bar{Q}\,\Omega}$$

hth harmonic:
$$\boxed{\frac{\partial\tilde{U}\big|_h}{\partial\chi}\Omega}+\boxed{I\omega_h\tilde{U}\big|_h\Omega}+\sum_{\text{Cell faces}}\left(\boxed{\tilde{\vec{F}}_C\big|_h}-\boxed{\tilde{\vec{F}}_V\big|_h}\right)\bullet\vec{S}=\boxed{\tilde{Q}\big|_h\,\Omega}$$

3.3 Flexible structure model

Blade structure is represented by its natural frequencies and mode shapes determined outside the flow solver either by computation with a FEM structure solver or by experiments.

The elastic body deformation under the fluid loads is obtained by a linear structural solver integrated inside the CFD solver.

$$\frac{\partial^2 q_k}{\partial t^2}+2\xi_k\omega_k\frac{\partial q_k}{\partial t}+\omega_k^2 q_k=\vec{\phi}_k\bullet\vec{f}_S$$

For 2 way FSI coupling using the NLH base line formulation, the modal representation is rewritten in a harmonic context by expressing q_k (generalized displacements) by means of time-averaged and fluctuations.

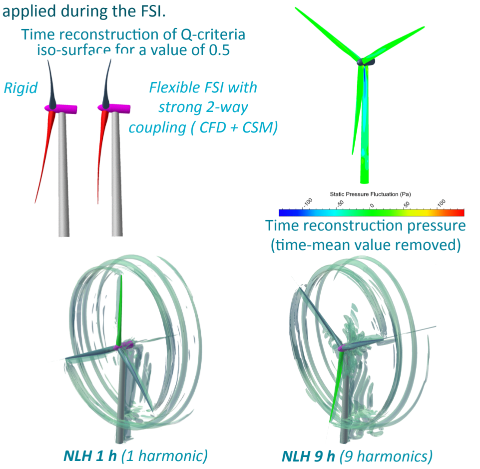
$$q_k(\vec{x},t)=\bar{q}_k(\vec{x})+\sum_n q''_{k,n}(\vec{x},t)$$

$$\bar{q}_k=\frac{\vec{\phi}_k\bullet\bar{\vec{f}}_S(\vec{x},t)}{\omega_k^2}$$

$$\tilde{q}_k\Big|_h=\frac{\vec{\phi}_k\bullet\tilde{\vec{f}}_S\Big|_h}{\omega_k^2-\omega_h^2+2I\xi_k\omega_k\omega_h}$$

4. Results

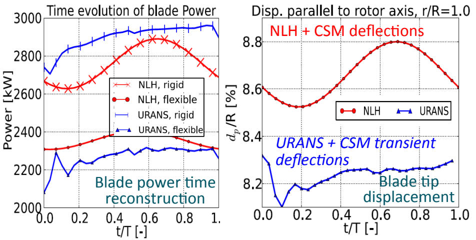
The FSI methodology performances are illustrated on DTU-10MW Reference Wind Turbine (Bak et al., 2013). The flow meshes of the assembly were automatically generated with Autogrid5^{TM}. The hybrid RBF+TFI mesh deformation is applied during the FSI.



Time reconstruction of Q-criteria iso-surface for a value of 0.5
Rigid
Flexible FSI with strong 2-way coupling (CFD + CSM)
Time reconstruction pressure (time-mean value removed)
NLH 1 h *(1 harmonic)*
NLH 9 h *(9 harmonics)*

	Unsteady flow Solved in the Frequency Domain with NLH				*Unsteady flow Solved in the Time Domain with URANS*
	1 h	*3 h*	*6 h*	*9 h*	
10^6 nodes	13	13	13	13	25
CPU time	1/2 day	1 days	2 days	5 days	≈52 days

Data corresponds to 128 procs @2.6 GHz



NLH refers to NLH solution in the frequency domain of the URANS
URANS refers to integration in the time domain of the URANS

5. Conclusions

In HAWT applications RBF+TFI and RBF+TFI+ELA mesh deformation are 5 and 3 orders of magnitude faster than previous methods.

2-way coupling NLH FSI method enables to capture complex unsteady aerodynamics and aeroelastic phenomena.

Aeroelastic FSI reduce time-averaged power of DTU HAWT by ≈16% with a relative rotor power oscillations of ≈2%. The aero-elasticity also attenuates dynamic loading fluctuations.

A good correlation between the frequency domain NLH URANS and time domain URANS is observed while saving CPU cost from 52 days (time URANS) to <5 days (NLH URANS).

6. References

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5. Vilmin, S., Lorrain, E., Hirsch, C., and Swoboda, M. (2006). Unsteady Flow Modeling Across the Rotor/Stator Interface Using the Nonlinear Harmonic Method. GT2006-90210 In *ASME Turbo Expo*, Barcelona.