INRIA

AEROGUST Workshop
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Aero-elastic study of a wind turbine subjected to a gust

Development of high-fidelity aero-elastic models
(WP2 and WP5)

Development of Reduced Order Models
(WP4)
Development of high-fidelity aero-elastic models

Fluid dynamics

• **Cartesian immersed boundary code**
  • Used for preliminary testing (aeroelastic coupling, wall functions for deforming bodies,...)

• **Adaptive octree immersed boundary code**
  • Devoted to full scale simulations
  • Under development during the PhD of Claire Taymans as a collaboration between VALEOL and INRIA
  • Discretisation and parallelisation based on the BitPit library developed by Optimad
Fluid dynamics

Single blade simulation with cartesian code

The cartesian Navier-Stokes solver is used as a testbench to explore the following topics which will be then exploited for the adaptive octree solver:

- Rotational frame of reference: introduction of centrifugal and Coriolis forces in the fluid solver
- Full coupling between fluid solver and structural model (bending/axial/torsion beam discretised with finite element)
- Wall function for under-resolved boundary layer
- Vreman subgrid model for Large Eddy Simulations

(Vorticity evidenced by q-criterion)
Fluid dynamics

Wall functions (WFs) for high-Reynolds number flow

The Reynolds number on the full scale turbine (w.r.t. the blade chord) is high ($10^6$): wall modeled Large Eddy Simulations (with subgrid model of Smagorinsky, Vreman, …)

- Implementation in the framework of immersed boundary methods
- Direct forcing: the solution is corrected in the first fluid points close to the wall
- The corrected solution could introduce an error on the velocity divergence
- Deforming/moving bodies
Development of high-fidelity aero-elastic models

Structural model

Two beam models have been implemented to describe the deformation of the blade:

- 1D beam model for bending with geometrical non-linearity. Explicit time integration
- 1D beam model for linear bending, torsion, axial deformation with coupling between bending/torsion and bending/axial deformation. Implicit time integration (Newmark method)

(Deformation amplified for visualization)

Theoretical and predicted bending natural frequencies
Development of Reduced Order Models for accelerating CFD predictions

Work done in collaboration with OPTIMAD

- Perform several full CFD simulations for different values of the parameters
- Build a Proper Orthogonal Decomposition (POD) basis with these simulations
- Predict the behavior of the system for a new value of the parameters by using low cost hybrid simulations

Hybrid simulations

### Poisson POD solver for incompressible solver

The Poisson problem in the correction step of incompressible solvers can be quite time consuming. Use a POD basis to get a cheap solution of the Poisson problem (or to get a good initial guess): do not alter the other functions in the CFD solver.

### Domain decomposition

A CFD solver is used to compute the solution in a small region which is strongly influenced by the effects of the change in the parameter space while the external field is described by a POD basis.

General purpose approach (compressible/incompressible equations, steady-unsteady problems,...)
Domain decomposition: dynamic coupling between CFD and POD

Work done in collaboration with Optimad

- The POD model is used to define the boundary conditions for a reduced CFD domain
- The non-linearities which are difficult to describe by POD and the phenomena not included in the database are directly taken into account by the CFD solver

\[ U_{ROM}(x, t) = U_{avg}(x) + \sum_{i=1}^{N} a_i(t) \Phi_i(x) \]

The coefficients of the POD expansion \( (a_i) \) are computed by minimizing the distance between the CFD solution and the POD expansion in the overlapping region at each time step:

\[ \min \left( \| U_{CFD} - U_{ROM} \|_{\Omega_o} \right) \]

Introduction of forcing terms for gust simulations:

\[ U_{ROM}(\mathbf{x}, t) = U_{avg}(\mathbf{x}) + U_g(\mathbf{x}, t) + \sum_{i=1}^{N} a_i(t) \Phi_i(\mathbf{x}) \]

Approximated forcing term: POD introduces corrections

**Updates after previous meeting:**

- Leave-one-out strategy for the choice of the CFD region
- Study on the choice of the overlapping region
- \( U_{avg} \) fixes the far field value
- The modes are zero in the far field: far field values automatically satisfied (e.g. Re, Mach,...)
- Two completely independent models, one for velocity and one for pressure
Domain decomposition: how to choose the high-fidelity region?

- Application to an airfoil-vortex interaction problem
- Parameters of the problem: vortex intensity and size
- Evaluate a prediction error indicator by using a leave-one-out strategy (following the work done by OPTIMAD)

Leave-one-out strategy (1)

- Create a database of high-fidelity simulations
- For(i=1, Nsim){
  - Remove the i-th simulation from the database
  - Use the remaining simulations to build a POD basis
  - Use the obtained POD basis to reconstruct the missing simulation and to evaluate the i-th prediction error
- }
- Take the maximum of the prediction error between all the cases in order to define the prediction error map

The high-fidelity description will be limited to the region where the error is larger than a given threshold
Sampling of the parameter space and choice of the high-fidelity region

- Choose a set of sampling points in parameter space
- Evaluate the prediction error indicator map
- Set a threshold on the error and define the high-fidelity region for the hybrid simulation
- Is the high-fidelity region too large? Improve the database
Domain decomposition: how to choose the overlapping region?

The error map \((e(x))\) previously defined can be used to choose the overlapping region. If the POD basis cannot reproduce the solution in a region it could be better to exclude that region from the overlapping zone:

Overlapping region : \(\Omega_o = \{x: e(x) < \sigma_o\}\)

where \(\sigma_o\) is a threshold which can be defined by an offline analysis of the database with a leave-one-out strategy.

The choice of the overlapping region will be optimised according to the chosen goal function.

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### Leave-one-out strategy (2)

- Create a database of high-fidelity simulations
- For\((i=1, N_{sim})\)\{
  - Remove the \(i\)-th simulation from the database
  - Use the remaining simulations to build a POD basis
  - For\((\sigma_o = \sigma_o^{\text{MIN}}, \sigma_o^{\text{MAX}})\) \{
    - Choose a threshold \(\sigma_o\) and define the corresponding overlapping region
    - Use the obtained POD basis to perform an hybrid simulation and to evaluate the prediction error on a given goal function
  \} \}
- Identify the overlapping region which gives (in average) the minimum prediction error
Domain decomposition: how to choose the overlapping region?

Prediction error as a function of the overlapping zone for two different goal functions:

Goal function: maximum lift coefficient

Goal function: L2-norm of the error on the lift coefficient during the considered time interval
Domain decomposition: prediction of a new configuration out of the database
Domain decomposition: prediction of a new configuration out of the database

The results of a reference CFD simulations are compared with hybrid simulations for different overlapping regions.

The behaviour is inline with the offline analysis of the database which can be used to choose the best overlapping region according to the desired goal quantity.
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