A preCICE-OpenFAST adapter to couple OpenFAST to CFD simulation tools

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- **Flow dynamics in wind parks are important for many engineering problems from optimized control to load reduction**
- **High-fidelity flow computation, eg in OpenFOAM, is desirable to understand the farm flow dynamic**
- **Low-fidelity simulation of the wind turbines is often sufficient**
- **OpenFAST allows to simulate one or multiple turbines in low fidelity**
- **I present a preCICE-OpenFAST adapter to couple OpenFAST to the coupling library preCICE**
- **preCICE couples simulation programs in a black-box manner to achieve multi-´physics simulations**
- **The adapter serves as driver code for OpenFAST to steer the simulation and calls preCICE for the data exchange**
- **As a first proof of concept, a coupling to OpenFOAM with limited capabilities is presented**

I. Introduction

The realistic representation of the flow around wind turbines and larger wind parks can have a valuable impact on many fields. In engineering, it enables the optimization of turbine design and control to minimize structural loads and maximize power outputs. Economic assessments of the cost of wind energy production rely on a thorough understanding of how much energy a wind park will produce, and how often load-induced maintenance and replacements are necessary. Policy makers and planners are interested in the local environmental effects from acoustics to microclimates to regulate the placement of wind parks effectively.

To gain understanding of the aerodynamic effects of wind turbines, simulation tools are invaluable as they allow to study numerous conditions and arrangements without the need of complex experiments. However, the simulation of fluid dynamics at the scale of wind turbines or whole wind parks comes with a considerable trade-off. Detailed, high-fidelity simulations may capture the physics of the problem accurately, but are computationally very expensive. An alternative can be found in low-fidelity engineering models which model the physical phenomena in a simplified way to represent the most important aspects of the problem at hand. A popular engineering model for the fluid-structure interaction of wind turbines is the Actuator Line Method (ALM). The turbine tower and blades are represented as slender beams or lines, reducing the number of computational nodes. Nevertheless, it allows the detailed study of blade deformations and wake effects. A widely-used tool implementing the Actuator Line Method is the wind turbine simulation software OpenFAST[1]. Coupling OpenFAST with a high-fidelity CFD solver allows to accurately solve the wind field at moderate computational cost. The CFD program computes a detailed large-scale flow field and exchanges the local flow velocity with OpenFAST (see Fig. 4). OpenFAST computes the turbine dynamics and sends back forces

[1] `https://openfast.readthedocs.io/en/main/`

and deflections which are imposed on the flow field. The challenge in this setup lies in implementing the data exchange and mapping while ensuring numerical robustness of the simulation.

One solution to this problem is the open-source tool preCICE. preCICE is a coupling library for multi-physics simulations and allows to couple different programs to perform a partitioned simulation. It takes care of the communication and data mapping between the tools and implements different coupling schemes. To connect a program to preCICE, an additional piece of software called adapter is necessary. Once a simulation tool is connected to preCICE, it can be coupled to any other program in the preCICE environment, reducing the time-to-solution. The main idea of this work is therefore to develop a preCICE-OpenFAST adapter to couple OpenFAST to CFD simulation tools via preCICE.
To provide context, chapter II provides a literature review on the existing couplings between OpenFAST and several CFD solvers. The software packages used as well as the concept of the newly developed module are then described in Chapter III. Chapter IV outlines two test cases on which the software is applied, followed by a description of the development challenges the software still faces to reach maturity in chapter V. The final chapter VI concludes on the current capabilities and future possibilities of this approach.

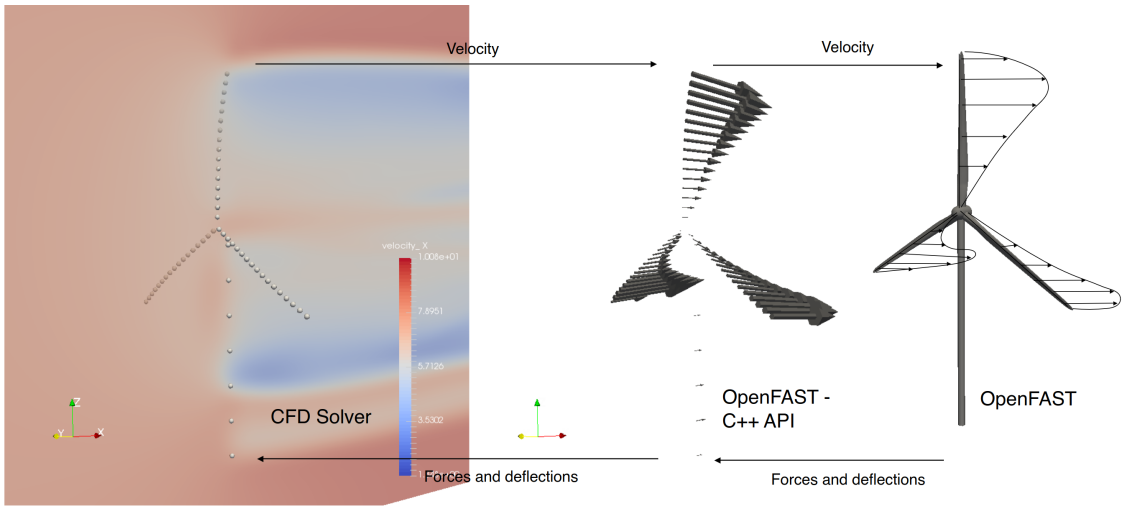


Figure 1. Coupling of OpenFAST to a CFD program. The fluid solver computes the flow dynamics and sends velocity data to OpenFAST. OpenFAST simulates the turbine dynamics and sends back forces and deflections, which are imposed on the flow field. Source: OpenFAST documentation[2]

II. Literature Review

A recent advancement in the coupling of OpenFAST is the tool **AspFAST** [8]. Developed at the Delf University of Technology and the weather forecasting company Whiffle, it connects OpenFAST to the closed-license Large Eddy Simulation (LES) code GRASP. As a binder code, AspFAST serves as an intermediary between the GPU-driven GRASP and the CPU-driven OpenFAST. It accesses OpenFAST through a C++ API, essentially operating as a driver code. GRASP is accessed through a specialized API that handles the transition from CPU to GPU operations. The core functionalities of AspFAST include the data exchange and mapping between GRASP and OpenFAST. This is done for crucial data such as force, velocity, and the position of turbine blades. Notably, the code implements the mapping between the volume-based velocity grid of GRASP and

[2] `https://ganesh-openfast.readthedocs.io/en/latest/_images/actuatorLine_illustrationViz.pdf`(visited on 07.11.2023)

the actuator line model of OpenFAST. Because the coupling code[3] is open-source, it can serve as a blueprint for anyone interested in coupling OpenFAST via the C++ interface. The software architecture of AspFAST is not far from our idea for the preCICE-OpenFAST adapter: AspFAST is a plug-in for the CFD solver GRASP while being the driver code for OpenFAST, serving as the "adapter" between the two. A big difference lies in the fact that AspFAST also has to implement the mapping algorithms, which are executed by preCICE in our approach.

The **ExaWind** project [7] is based on the open-source, massively paralles and incompressible flow solver NaluWind [1]. It is a wind-focused adaption of the general flow solver NaluCFD and strives to deliver flow simulations in exascale. Hence, great emphasis lies on the scalability and simulation speed of the software through advanced solver and coupling algorihtms as well as the use of GPUs. The coupling to OpenFAST is implemented inside NaluWind and not as additional plug-in. An extensive documentation with insights into the theory and verification is given.

Another coupling based on solver modification is the Simulator for Wind Farm Applications or **SOWFA** [4] from NREL. It couples OpenFOAM to OpenFAST by providing an additional class *horizontalAxisALM* in OpenFOAM. It defines functions to call OpenFAST and enables the data exchange. This class can be included directly in any OpenFOAM solver by modifying the OpenFOAM source code, so that the solver calls OpenFAST during each time step.

A software solution relying on a similar coupling tool to preCICE is **foamFAST** [9]. This project uses the commercial coupling tool for partitioned multi-physics simulations MpCCI, developed and sold by the Fraunhofer SCAI. Similar to preCICE, MpCCI is connected to different programs via adapters. Once the adapter is written, you can couple your tool to any other tool in the MpCCI environment. A difference in software architecture is the fact that MpCCI acts as the master algorithm: It calls the solvers instead of being called by them like preCICE. During the project, a MpCCI adapter for OpenFAST was developed and an existing OpenFOAM adapter modified to perform the coupling between the two.

The reviewed literature shows two different concepts to undertake the coupling. The first idea is to **modify the CFD solver source code**, as the ExaWind project has done with the NaluWind solver and SOWFA with OpenFOAM. While convenient for developers who are familiar with the software, this approach can prove hard to maintain when the underlying solver software is updated.

The second concept leaves the CFD solvers intact and uses **an additional software layer** to connect the simulation tools. One way to implement this is the library approach where an additional module or library is called by the original CFD solver. An example is AspFAST, where the stand-alone plug-in code is maintained seperately from the solver. The second way for implementation is the framework approach, used by the coupling tool MpCCI in foamFAST. Here, the additional software acts as a master algorithm calling the solver.

Given the previous work, why should we continue to develop a preCICE-OpenFAST adapter? Our approach combines some of the positive aspects of previous projects. First, preCICE follows the library approach, leaving the original programs untouched and enabling a fast time-to-solution. Using preCICE allows to rely on advanced and tested coupling algorithms without the need to re-implement them or buy a licensed software. Establishing a preCICE-OpenFAST adapter opens up the road to connect OpenFAST not only to OpenFOAM, but to any CFD solver coupled to preCICE. Furthermore, preCICE creates a clean and easy to use simulation environment and simplifies setting up and maintaining simulations.

Nevertheless, it should be noted that OpenFOAM is currently the only CFD solver connected to preCICE which can be used for a coupling with OpenFAST. Coupling any other tool, such as the presented GRASP or NaluCFD, will require the development of additional adapters.

[3] `https://gitlab.com/whiffle-public/aspfast` (visited on 20.12.2023)

III. Software description

A. Software components

1. preCICE

preCICE [3] is an open-source coupling library for partitioned multi-physics simulations. An overview of its concept is shown in Figure 2. In preCICE terminology, the coupled simulation programs are called *solvers* or *participants*. preCICE connects different solvers to perform a partitioned simulation. It takes care of different coupling aspects such as data mapping and communication. Different coupling schemes are possible [5] by the choice of which solvers are coupled, what data is exchanged and which coupling algorithms are used. Explicit and implicit coupling schemes are available, as well as the option to connect more than two participants via multi-coupling. In addition, preCICE provides acceleration algorithms to reach a decent computation time for large simulations and time interpolation for the coupling of solvers with different time steps. The coupling scheme is defined in the *precice-config.xml*, the only global file which is accessed by all participants.

For each solver, a specific *adapter* is necessary to communicate with preCICE. The adapter is an additional software layer which can take many forms, depending on the solver. For example, the OpenFOAM adapter is a C++ function object, an independent library, while the FEniCS adapter is a Python module. Additional language bindings in Fortran, Julia and Matlab allow the development of adapters in these languages as well.

Additional remarks: library approach, scalability, HPC

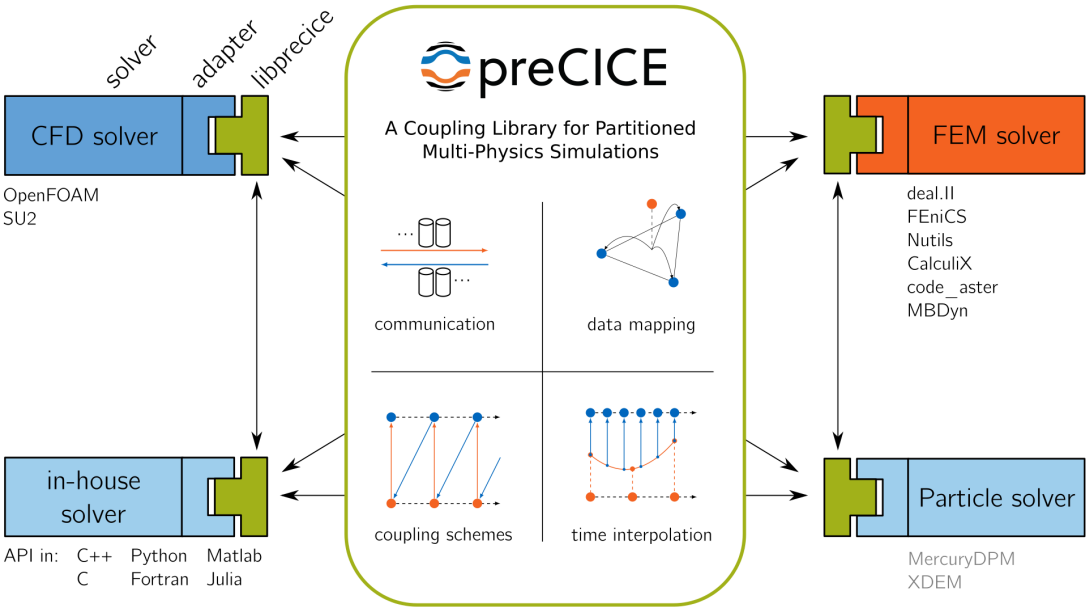


Figure 2. preCICE overview [3]

2. OpenFOAM and the preCICE-OpenFOAM adapter

OpenFOAM is a popular open-source PDE tool with a long history. It enables the use and modification of different solver algorithms and is used mainly for CFD simulation, but also for FEM problems and in heat transfer.

- OpenFOAM

  - Popular open-source PDE tool in academia and industry
  - Enables the use and modification of different solvers
  - Used mainly for CFD but also FEM simulations
- Adapter
  - Enables the coupling of OpenFOAM via preCICE in different simulation scenarios
  - Exemplifies the development strategy behind preCICE: Adapter is a library for OpenFOAM and called on runtime to perform the coupling without any modification to the OpenFOAM source code
  - Different modules for different kinds of multi-physics simulations: FSI, FF, CHT

Note: I should introduce the OpenFOAM adapter at some point. Lets introduce the broad concept of the adapter here and add more details, eg about the specific files that would need to be modified, later in the Challenges part

3. OpenFAST

OpenFAST[4] is a wind energy engineering tool developed by the NREL. It is widely used in academia and industry to simulate the coupled aerodynamic, structural, and electrical behaviour of wind turbines as well as the control response. The tool allows to model on- and offshore wind turbines and can be used to simulate wind parks consisting of multiple turbines as well. On a software level, OpenFAST is a glue code for different modules which compute the various physical domains. For example, the separate module AeroDyn is used to compute the aerodynamics of a simulation case and coupled to the ElastoDyn module, which computes the structural response. Additionally, it provides a C++ API to drive the simulation and compute the wind field in an external CFD tool. OpenFAST takes one main input file denoted *.fst* which holds simulation metadata and points to more specific input files for each computation module.

B. Software concept

The main idea of this work is to develop a preCICE-OpenFAST adapter, a new piece of software that connects OpenFAST and preCICE. It acts as a driver code towards OpenFAST, leveraging the C++ API of the simulation program. Simultanously, it calls preCICE to communicate data and receive steering commands for the simulation. The software is configurable on runtime by two *.yaml* input files. *preciceInput.yaml* contains information about the coupling setup such as which variables are exchanged, which meshes are used and where the global *precice-config.xml* can be found. *openfastInput.yaml* adds metadata for the wind turbine simulation and points towards the OpenFAST *.fst* file.

The software concept is presented in simplified form in Figure 3. First, the header files for important libraries are included and variables for data handling are created (lines 1-5). The script then utilizes the C++ API of OpenFAST and preCICE to instantiate and initialize both tools (lines 8-14). The *FAST* object allows the access of OpenFAST while the *participant* object is connected to preCICE. The coupling library controls the main time loop (line 1628) which performs the coupled simulation. First, velocity data is retrieved from the CFD solver and stored locally (line 18). The information is then passed on to OpenFAST (line 20) and updated on the internal meshes of the simulation tool. OpenFAST is called to compute the wind turbine dynamics for the next time step (line 22). The resulting blade and tower force data is extracted and stored (line 24). The updated force data is passed on to the CFD solver (line 26), after which both solvers advance in time (line 28). This loop is repeated until the simulation time is completed. Finally, preCICE and OpenFAST are destructed (lines 30-31). The software is developed and documented on GitHub[5].

[4] https://openfast.readthedocs.io/en/main/

[5] https://github.com/LeonardWilleke/openfast-adapter

```
#include <OpenFAST.H>
#include <precice.hpp>

vector<double> readData;
vector<double> writeData;

// OpenFAST Setup
fast::OpenFAST FAST;
...
FAST.init()
// preCICE Setup
participant = precice.participant(...);
...
participant.initialize();
// main time loop
while participant.isCouplingOngoing():
        // Get read data from preCICE
        participant.readData(readData, ...);
        // Set read data in OpenFAST
        FAST.setVelocity(readData, ...);
        // Compute next time step
        FAST.step();
        // Get write data from OpenFAST
        FAST.getForce(writeData, ...);
        // Send write data to preCICE
        participant.writeData(writeData, ...);
        // Advance preCICE in time
        participant.advance(dt)

participant.finalize()
FAST.end()
```

Figure 3. Concept of the OpenFAST adapter: The script utilizes the C++ API to execute OpenFAST and calls preCICE to couple the simulation. For conciseness, API calls are simplified.

IV. Example cases

To drive the adapter development and test the software at its current state, two example cases were implemented. The OpenFAST simulation of a single wind turbine, namely the NREL 5MW model [6], should be coupled. The first case couples the simulation to a dummy fluid solver. While performing no realistic computations, the dummy is handy to get an insight into the different data structures, mesh setups, and mapping options. The second case couples OpenFAST to OpenFOAM. It can be seen as a first proof-of-principle with a successful data exchange between the tools. However, more work needs to be done to ensure a correct and robust simulation. Both cases are part of the repository on GitHub[6].

[6] https://github.com/LeonardWilleke/openfast-adapter/tree/main/cases

A. Coupling OpenFAST with a dummy CFD solver

The reasoning behind this case is to provide a simple and fast way to test different functionalities and gain insight, not to perform realistic simulations. OpenFAST computes a NREL 5MW turbine with a fixed rotor to avoid mesh problems on the moving blades. The fluid solver is implemented as a simple C++ script that calls preCICE to enable the coupling. It creates a mesh that can be used to map data from OpenFAST on it and writes constant values back, but does not perform any calculations. The setup allows to explore the mapping and data exchange.

OpenFAST employs two internal meshes of the turbine surface with different vertices. Force data is stored on one mesh, while the flow velocity is stored on another. Both meshes can be accessed by the C++ API. However, it is also possible to exchange both variables with the velocity mesh and let OpenFAST map the force data to the force mesh internally. Inspired by the coupling setup in [8], I want to access both meshes and use preCICE for the mapping. This results in the elaborous coupling scheme seen in Figure **??**. In total, three meshes are employed: The Fluid solver has one mesh *Fluid-Mesh* used for both the force and velocity data while the Solid solver (OpenFAST) uses two meshes. *Solid-Mesh-Velocity* is the velocity mesh of OpenFAST, on which the velocity data from the Fluid solver is mapped. *Solid-Mesh-Force* is the force mesh of OpenFAST, from which force data is mapped back to the Fluid solver.

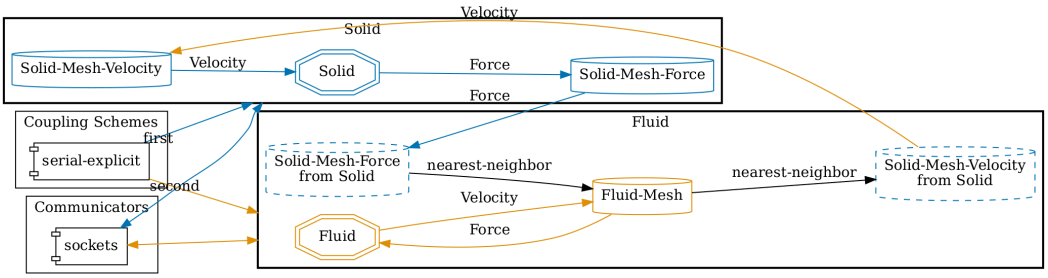


Figure 4. Coupling scheme between OpenFAST, named Solid, and the dummy Fluid solver. The figure was created from the *precice-config.xml* using the *config visualizer tool*[7].

B. Coupling OpenFAST with OpenFOAM

The coupling of OpenFAST with OpenFOAM uses the same coupling scheme as presented in the previous case. However, we are dealing now with

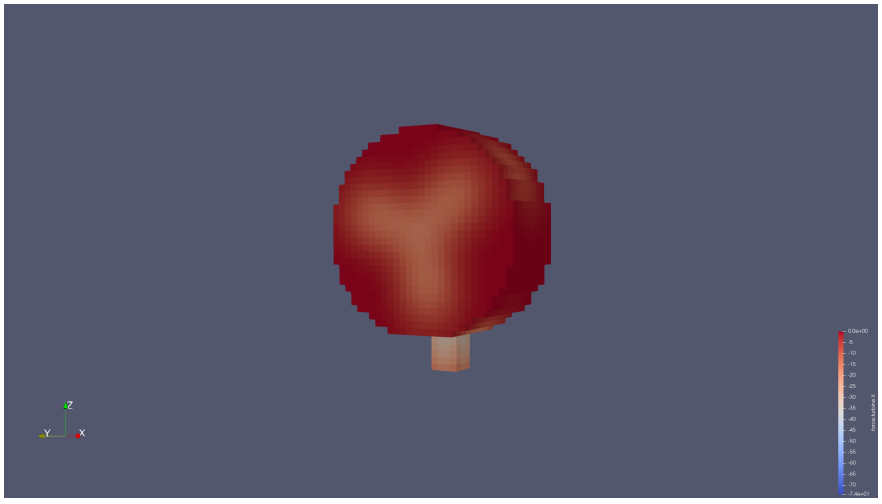
Case cfd-turbine

- Explain the setup
  - Couple OpenFAST to OpenFOAM
  - The coupling scheme and mesh use is identical to the dummy
  - Now we are dealing with a different mesh on the fluid solver
  - Main obstacle: The OpenFOAM adapter is not designed to implement a coupling with a solver using the actuator line method. How to map between the line mesh in OpenFAST (Figure)5a and the volume mesh in OpenFOAM (Figure 5b)?
- Explain how the current setup works
  - Define a cellSet inside the OpenFOAM domain (Figure 5b) to which OpenFAST is coupled
  - Write the rotor and tower data to this subdomain
  - Read velocity data from this subdomain

[7] `https://precice.org/tooling-config-visualization.html`

  - The mapping from line to volume and back is done by preCICE, but probably wrong
- How should the turbine be represented in OpenFOAM?
  - Volume mesh / cellSet
  - Surface mesh / patch
  - ALM implementation (eg with turbinesFoam)

(a) Line representation of the turbine in OpenFAST



(b) Volume representation of the flow field immediately around the turbine in OpenFOAM

Figure 5. Mesh differences between OpenFAST and the CFD solver OpenFOAM. OpenFAST uses the Actuator Line Model to represent blades and towers in the flow field, while OpenFOAM calculates the whole flow field.

V. Challenges

Current limitations of the adapter

- Only for one turbine
- Only for onshore turbine
- Only proof of concept: Data is exchanged in a sensible way, no knowledge about the physical correctness

What are the next steps in the coupling of OpenFAST via preCICE?

Task 1: Mapping turbine data between actuator lines and volume meshes

- Problem: The OpenFOAM adapter is not designed for the implementation of ALM

- We need to get velocity from a volume section –> possible
- We need to set force or pressure gradient on a volume section –> not possible
- Solution 1: Do the mapping in the OpenFAST adapter
  - Something very similar has been done by AspFAST (LINK)
  - Includes smearing of the actuator data which is good
  - Possible Problem: I add volume data to the mesh in the OpenFAST adapter that the OpenFOAM adapter is not able to write to FOAM afterwards –> think about
- Solution 2: Modify the OpenFOAM adapter
  - Adapt the PressureGradient.C class of the FF module
  - Include code to write pressure gradient on a cellset
  - Take structure from Pressure.C class
  - Problem: How to write the pressure gradient on a field in OpenFOAM?
  - Pressure gradient seems to be the boundary condition of the velocity field U –> this is settable
  - Requires the correct import of the velocity field and the correct retrieval of its boundary field –> give the commands you know
  - Not sure if you can also set the pressure gradient on the pressure field itself but dont think so
  - Open: How to do smearing if necessary

Task 2: Bring the OpenFAST adapter to maturity
- Write a regression test (using the dummy fluid solver)
- Create a first test case with documentation
- Verify simulation results against simulations done with AspFAST and other tools ([8] gives some benchmark cases)

Task 3: Enable coupling with multiple turbines
- OpenFAST C++ API allows to run multiple instances of OpenFAST for wind park scenarios
- How do you connect them to preCICE?
- How do you define the different coupling scenarios?
- Possibly use the MacroMicro manager of preCICE to deal with the coupling of multiple domains

Task 4: Explore coupling scenarios with other CFD solver
- Are there currently other CFD solvers coupled to preCICE that would be interesting?
- Otherwise interesting candidates are: YALES2, GRASP, NaluWind
- Most of them have native coupling tools for OpenFAST already

Additional remarks
- The OpenFOAM library turbinesFoam[8] [2] might be useful. It implements the actuator line method with different solvers like pimpleFoam in OpenFOAM. The solvers are modified to perform the ALM computation. It is not clear yet how this could be of use, as we want to perform the ALM computation of the turbine to OpenFAST and map the results to OpenFOAM, not do the whole computation in OpenFOAM.

VI. Conclusion

A first preCICE-OpenFAST adapter to couple the wind energy engineering tool to CFD solvers was presented in this work. The coupling of an OpenFAST simulation of a single wind turbine with a dummy solver and OpenFOAM was discussed. Although a proof of concept was achieved, showing that preCICE can be used

[8] `https://github.com/turbinesFoam/turbinesFoam` (visited 14.12.2023)

for the coupling to OpenFOAM in principle, some challenging tasks remain. The coupling of OpenFAST to an arbitrary CFD solver was not discussed and poses more questions. This work may serve as a starting point. The presented preCICE-OpenFAST adapter has the potential to be developed into a viable open-source alternative for the coupling of OpenFAST to different CFD solvers.

Acknowledgments

I am grateful to Prof. Axelle Viré who accepted me as a visiting researcher and made this work possible. Many thanks to her and Evert Ewald for the discussions and hints during our meetings. Extended thanks to Benjamin Uekermann, who enabled my visit at TU Delft in the first place and provided feedback along the way. Lastly, I want to thank the wonderful crowd of PhD researchers in the wind energy department who made my time in Delft memorable.

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Appendix

Possible points to include in the Appendix

- Files from the OpenFOAM adapter with hints on how to modify them
- Files from AspFAST with hints on how to reuse the code for our mapping