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Parallel Fluid-Structure Simulation of Cycloidal Rotors

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As an answer to rising traffic congestion in growing cities, Urban Air Mobility (UAM) is a mobility expansion into a safe and sustainable three-dimensional traffic solution. In particular Vertical Take-Off and Landing (VTOL) vehicles like air taxis or drones are expected to increasingly shape the mobility in future cities. Therefore, agility of aircraft will be a key criteria for vehicles traveling in crowded future urban air spaces, which is where the cycloidal rotor steps in. The concept of the cycloidal rotor as an aircraft propulsion system provides advantages in an increased maneuverability compared to conventional helicopters, while maintaining comparable efficiencies.

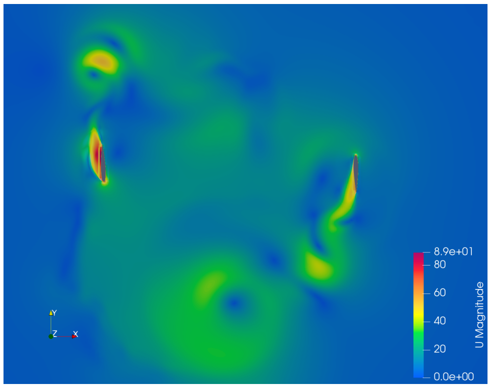

Figure 1: Velocity magnitude of a cycloidal rotor

However, the deformation of cyclorotor blades caused by aerodynamic forces and its effect on the rotor efficiency is not well understood. Also, air encounters the blade twice, once as it enters and once it exits the rotor. And, a dynamic stall behaviour and a blade-vortex interaction is favored in this system. Because the current state of the art Computational Fluid Dynamics (CFD) simulations of cycloidal rotors neglect the deformation of the blades [1, 2, 4], this considerable influence on the cyclorotor needs to be further investigated. A first approach into the topic of flexible cyclorotor simulations was done by Atanu and Moble [3], using the free wake method. Still further explorations are needed in this field, which is why the aerodynamic phenomena produced by a rotor are investigated by means of coupled numerical Fluid-Structure Interaction (FSI) simulation in this paper. A preview screenshot of the simulation results can be seen in Figure 1.

For the FSI setup, the CFD simulation software OpenFOAM[1] and the Multibody Dynamics (MBD) simulation software MBDyn[2] were used. These software tools were coupled using the coupling library preCICE[3], which provides connectivity to the mentioned solvers

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[1] OpenFOAM: `https://www.openfoam.com/`
[2] MBDyn: `https://www.mbdyn.org`
[3] preCICE: `https://precice.org`

with the OpenFOAM- and the MBDyn-Adapter. The OpenFOAM case is set up as a Reynolds Averaged Simulation with a k - ω SST model and a $Re_L = 725.000$ at the blades. PreCICE and OpenFOAM are optimized for cluster and local usage, which simplifies the transfer between the development and the working environment significantly. Therefore certain simulation performance tests on the 2D case with the chimera background mesh could be conducted on different numbers of processors (between 1 and 36 cores) on one node of the High Performance Computing (HPC) cluster at the Institute of Aerodynamics and Gas Dynamics (IAG) at the University of Stuttgart. The speedup evaluation after Amdahl's law provides a speedup which runs closely to the ideal value until OpenFOAM's critical limit of 10.000 cells per core is reached. From there on the speedup decays as expected.

In this paper, compatibility limits of the utilized software regarding the coupling of rotating bodies are discussed. In general the OpenFOAM-Adapter does only support the coupling of motion data via displacing determined bodies utilizing the `pointDisplacement` function. However, simulating rotating bodies a cyclorotor is not possible with this approach in OpenFOAM. Therefore an additional communication interface between the MBDyn-Adapter and the OpenFOAM-Adapter was set up to pass on information about the body orientation to OpenFOAM. With this tweak, the `solidBodyMotion` function can be used to perform rotations of the body. The regular force data and the displacement data, which handles the deformation of the rotor blades, is coupled using the provided adapters.

An issue of OpenFOAM was observed which leads to abnormal deformation behaviour of bodies when using the `solidBodyMotionFunction` and `pointDisplacement` together. To solve the mentioned issue a transformation operation was conducted. Moreover, a steering mechanism was added into the MBDyn model using an additional socket interface connected to the MBDyn-Adapter to control the thrust vector of the rotor.

Serial, parallel, explicit and implicit coupling methods are reviewed and evaluated for the given case. Furthermore, different mapping approaches provided by preCICE were tested. The Radial Basis Function (RBF) mapping method was chosen for the cyclorotor case setup. Benefiting from the offered mapping functionality of preCICE, the solvers can have different mesh qualities. This simplifies the MBDyn case setup, as the number of required nodes is reduced significantly. Finally the setup of a 3D simulated spanwise deforming cyclorotor blade is presented, which still has some mapping issues.

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