FLUID-STRUCTURE INTERACTION OF INFLATABLE WING SECTION

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1 Introduction

Airborne wind energy (AWE) is a concept for harvesting wind energy using tethered flying devices. Compared to conventional wind turbines AWE systems require substantially less support structures like a tower [1]. The replacement of towers by tethers also allow accessing higher altitudes where winds blow stronger and more persistent [2]. Several configurations are currently pursued. Electricity can be generated with on-board propellers which are driven by the air flow and the power is transmitted to the ground through a conducting tether. Another configuration is the pumping cycle in which case the kite flies crosswind to pull a tether that is unreeled as it moves a ground-based electrical generator, and a retraction phase when the kite is reeled in. Next to electricity generation AWE can also be used for ship propulsion.

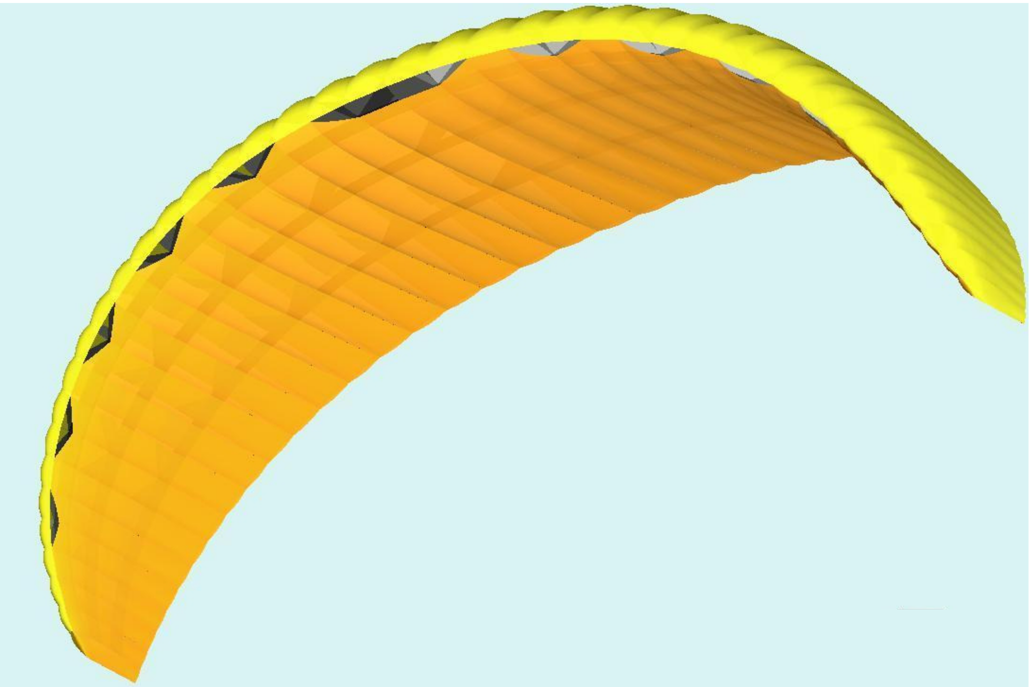

Figure 1: Ram-air kite layout [3]

We consider a single cell of a ram-air wing in our study which is based on an inflatable double skin design. As shown in Figure 1 ram-air wings are inflated by the stagnation pressure entering through inlets at the leading edge. The internal pressure provides structural stability and stiffness. The fully or partially inflated structure is flexible and can therefore exhibit large deformations during flight. This introduces a strong coupling between the structure and the air flow since the internal pressure in dependent on the wind speed, and a deformed kite will inevitably have a different pressure field caused by the flow compared to an un-deformed kite. Also, bridle system induces a significant additional drag to the wing drag and therefore the kites fly with high angle of attack to obtain high lift and to ultimately maximise power output. High angles of attack causes the flow to separate which cannot be simulated with fast inviscid methods and therefore a CFD analysis tool such as OpenFOAM is required.

The main challenge in analysis and design of these kites is the governing fluid-structure interaction (FSI) mechanism, which leads to a drastic increase in model complexity. On the other hand utilising FSI is crucial to obtain reliable results on performance measures and structural integrity. We follow the partitioned coupling approach, where the fluid and structure domains are solved individually and coupled at their interface. In this work we couple OpenFOAM with our finite element (FE) solver *mem4py* by using the coupling tool preCICE. The coupled solver is then used to simulate a single ram-air wing section (cell) and its change in aerodynamic performance due to deformation.

2 Methodology

The FE solver *mem4py* is an in-house development for inflated membrane structures with large deformations. The fabric's thickness used for soft kites is thin and therefore its bending and compressive stiffness is negligibly small. This assumption simplifies the shell formulation but comes with difficulties in numerical convergence for static equilibrium. The remedy is a dynamic formulation which simulates the structure with inertia and viscous terms. In our study we focus on finding a static equilibrium between structure and fluid to analyse the change in airfoil profile in span-wise direction as a function of angle of attack. Therefore the mass and viscous terms can be arbitrary and usually are chosen such that the structure is critically damped to quickly arrive at steady state configuration. This method is called dynamic relaxation [4], and is often applied in form-finding. On the other hand, the real dynamic structural behaviour can also be simulated by using realistic mass and damping parameters. This flexibility of the approach comes in handy for soft-kites because both static and dynamic behaviours can be simulated.

The aerodynamic loads are determined by CFD simulations using the FOAM-FSI library [5] which is an extension to the foam-extend project [6]. The FOAM-FSI library comes with several strong coupling algorithms for partitioned FSI problems, efficient mesh deformation solvers based on radial basis function (RBF) and an adapter to the preCICE coupling tool. The transient pimpleFoam solver is used together with the Reynolds Averaged Navier-Stokes (RANS) based SST k-ω turbulence model. The boundary layer around the airfoil is resolved to capture the flow separation and therefore an O-type mesh is generated with hyperbolic extrusion.

The two solvers are coupled using preCICE. It is an open-source library that comes with an extensive set of tools to couple existing solvers for partitioned multi-physics simulations. The strong (implicit) coupling schemes include several quasi-Newton variants to accelerate the convergence. The exchanged data is mapped for non-conforming meshes by using either consistent or conservative RBF. Both the coupling and the execution of the solver modules can be run in parallel.

Setting up a multi-physics simulation with preCICE requires a configuration file and implementing an adapter for each solver. The configuration file defines the general coupling parameters such as the names of the participating solvers, the exchanged data sets and the desired mapping and coupling algorithms. The adapter is a minimal piece of code which interfaces the solver modules with preCICE. The adapters can be implemented by using any of supported languages: C++/C, Fortran and Python. The simulation begins by executing each adapter individually with either serial or parallel execution. In this work we use the preCICE adapter in FOAM-FSI library to couple OpenFOAM and preCICE and we show how to implement the adapter for the structural solver *mem4py*. The implemented adapter contains less than 100 lines of code. Both adapters are implemented in the same programming language as the solver thus C++ for OpenFOAM and Python/Cython for *mem4py*.

3 Results

The FSI simulation framework is used to study the static aeroelasticity of a common ram-air kite airfoil MH 92 (Figure 2). The airfoil is extruded in span-wise direction and clamped at both ends. For simplicity no opening at the leading edge is introduced. Instead, a uniform stagnation pressure p_t is assumed inside the airfoil, and by superimposing internal and external pressure loads, no compressive forces act on the wing. The membrane has a thickness t and isotropic linear elastic material properties with Young's modulus of E and Poisson's ratio of ν. Typical flight conditions for a kite used for AWE generation are assumed with a Reynolds number of $Re_c = 5 \times 10^6$ and turbulence intensity of $I = 2\%$.

Expected results are a strong coupling between inflow conditions such as angle of attack and the deformed airfoil shape. Especially for high angles of attack the nose section experiences large pressure forces which deform the wing and completely change its drag polar compared to the un-deformed wing. Figure 3 shows cross-sections of the deformed kite shape experiencing an angle of attack of 10°. At mid span ($z = 0.5b$) the profile is considerably different than the initial shape ($z = 0b$). The nose section is dented inwards due to missing support from the ribs. The leading edge is pulled up and the whole section thickness is increased by nearly twofold.

4 Conclusions

Coupling existing solvers for partitioned multi-physics problems is straight-forward by using the preCICE tool. The implemented FSI framework is used to study a single cell of an inflated ram-air wing used in airborne wind energy. Drastic profile changes of the wing are observed and can only be resolved when incorporating a FSI routine into the analysis.

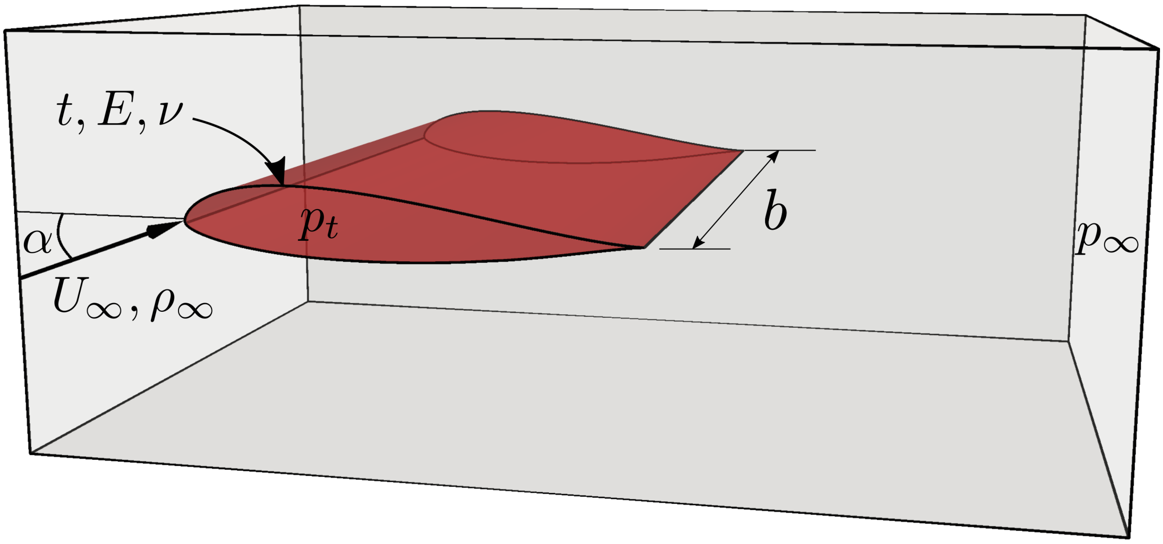

Figure 2: Inflated wing in virtual wind tunnel.

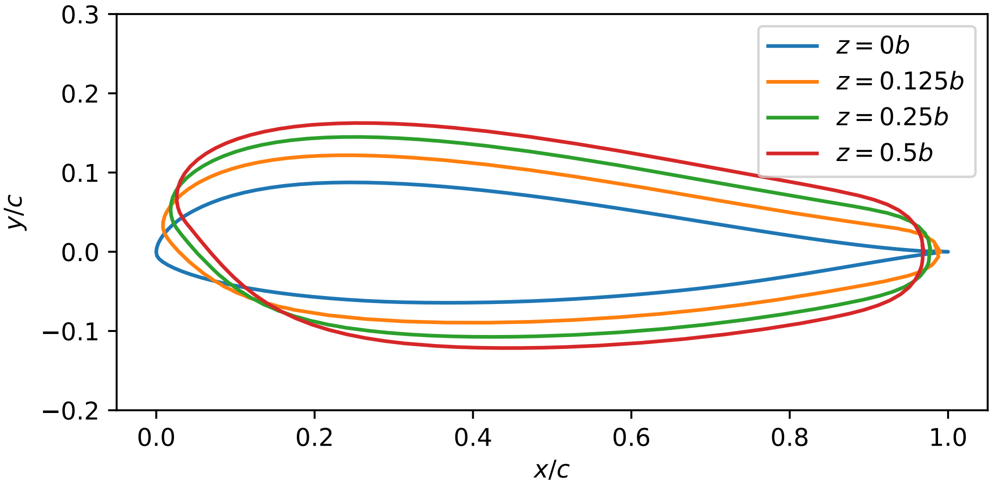

Figure 3: Cross-sections of the deformed inflated wing section at 10° angle of attack.

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