a tutorial paper by Doekemeijer et al. for the American Control Conference 2019, named "A tutorial on the synthesis and validation of a closed-loop wind farm controller using a steady-state surrogate model". This paper can be found in Section 7.2. The ZeroMQ control interface is described in section III.B therein.

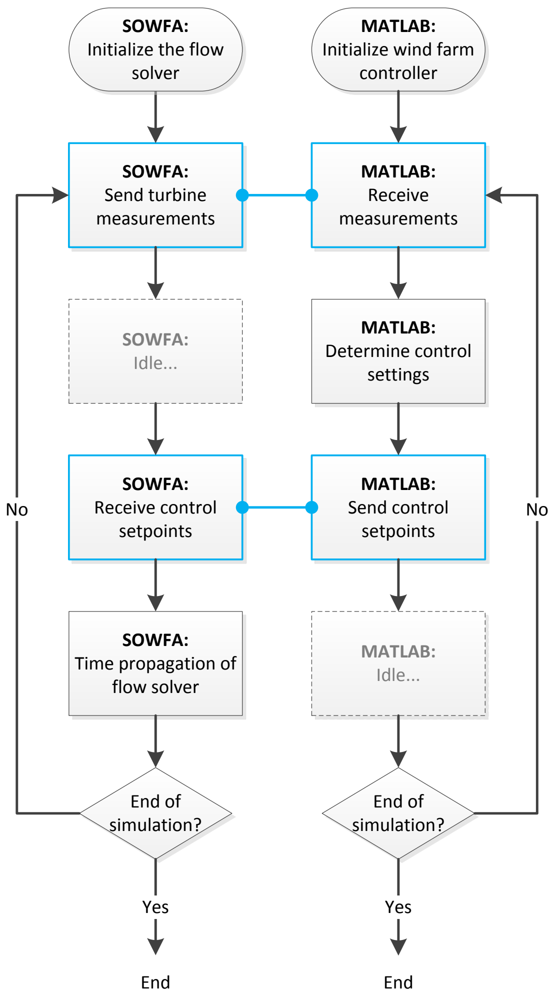

Figure 2. This figure shows a flowchart of the order of operations in a SOWFA simulation which is coupled to a closed-loop wind farm controller (in this case: implemented in MATLAB).

3.2 Implementation and validation of the InnWind 10MW turbine

One of the main goals of the CL-Windcon project is the demonstration of wind farm control algorithms on future-scale turbines. This will increase the relevance of the findings in this project for a longer period of time. Hence, the 10MW turbine developed by the Technical University of Denmark (DTU) from the InnWind project was chosen for simulations. An aero-elastic model was readily available of this wind turbine.

While the initial goal in the CL-Windcon project was to perform simulations in SOWFA coupled to the aero-elastic simulator "OpenFAST" to maximize the simulation fidelity, practical issues and unfinished software outside of the partners' control interfered with this process. As SOWFA simulations are key to the success of the project, TU Delft took it upon themselves to push for an implementation of the DTU 10MW turbine inside the advanced actuator line turbine model ("ALMAdvanced"), which is a turbine model inside SOWFA of comparable fidelity to OpenFAST in terms of rotor-flow interaction, yet neglects dynamics inside the hub and the displacement and deformation of the turbine structure, amongst others.

When translating the properties of the DTU 10MW turbine inside the SOWFA ALMAdvanced code, several discrepancies were noted. The turbine behaviour was compared across a range of performance measures:

1. The k-value in the wind turbine controller that achieves the highest power capture is between 1.0 and 1.3. This k-value is used in the $k - \omega^2$ control law in region 2 control. This is an important measure, as it ensures that the generator torque applied for a specific rotor speed is correct.
2. The tip-speed-ratio (TSR) belonging to this optimal k-value is approximately $\lambda = 7.5$.
3. The flow profile through the rotor disk should match roughly with actuator disk theory (in idealized SOWFA simulations without turbulence).
4. The mean power capture agrees with the literature for the assigned inflow wind speed.

Further, for numerical stability, the blade smearing factor ϵ was chosen at twice the cell size near the rotors, $\epsilon = 2\Delta x$. In addition, the timestep was chosen such that the Courant number, C, with

$$C = \frac{u\Delta t}{\Delta x}$$

never exceeded 1. With an inflow wind speed of 8 m/s in the simulations, the condition holds:

$$\Delta t \leq \frac{\Delta x}{8}.$$

Now, the spatial resolution Δx should be chosen in accordance to the desired resolution of the blade loads and the near-wake flow behaviour. This is demonstrated in Fig. 3.

Note that with $u = 8$ m/s, $\Delta t = 0.80$ s and $\Delta x = 5.0$ m, the Courant number is often exceeded, and thus may lead to instability for particular simulations. Decreasing the timestep under a constant Δx in this simulation improves stability results but does not allow for a correct turbine implementation. The remainder of this study is on the cases with $\Delta x = 2.5$ m and $\Delta x = 1.25$ m, respectively. From Fig. 3, one can see that the loads are slightly better modeled with $\Delta t = 0.05$ s and $\Delta x = 1.25$ m, though the dominant trends are still captured at $\Delta = 0.20$ s and $\Delta x = 2.50$ m.

A large number of simulations were run for different spatial and temporal resolutions and k-values. However, no satisfactory result was found in which all the aforementioned conditions were met. This

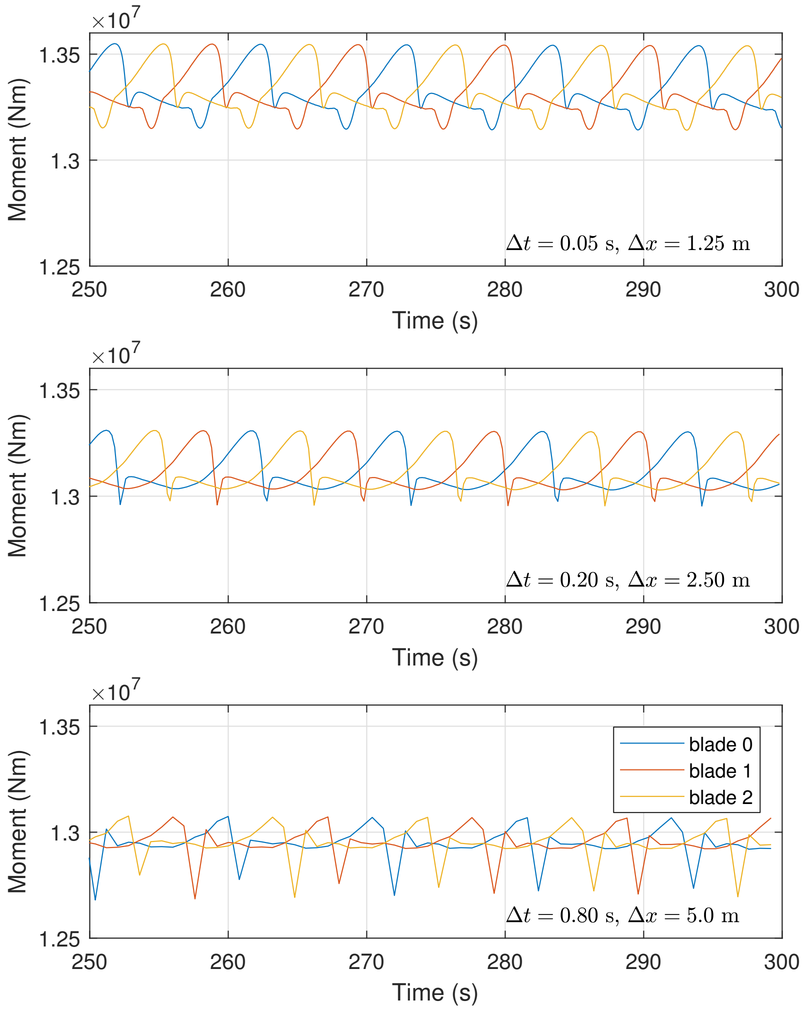

Figure 3. The effect of the spatial and temporal resolution on the smoothness and accuracy of the blade root out-of-plane bending moments

issue was addressed by introducing a new variable called, FORCESCALAR. This is a constant term close to 1 which linearly scales the lift and drag coefficient of each blade segment, according to

$$C_\ell = C_\ell \cdot \mathrm{forceScalar},$$

$$C_d = C_d \cdot \mathrm{forceScalar}.$$

The sensitivity of the power capture and the rotor speed (RPM) as a function of the FORCESCALAR value is shown in Figs. 4 and 5 for FORCESCALAR $= 1.15$ and FORCESCALAR $= 1.30$, respectively. From this figure, one can see that a higher value for FORCESCALAR $= 1.30$ shifts the optimal k-value upwards. The optimal k-value is chosen to be 1.15 with a FORCESCALAR value of 1.15, which yields both an optimal power capture compared to other k-values and matches the optimal TSR of $\lambda = 7.5$ as defined in the literature.

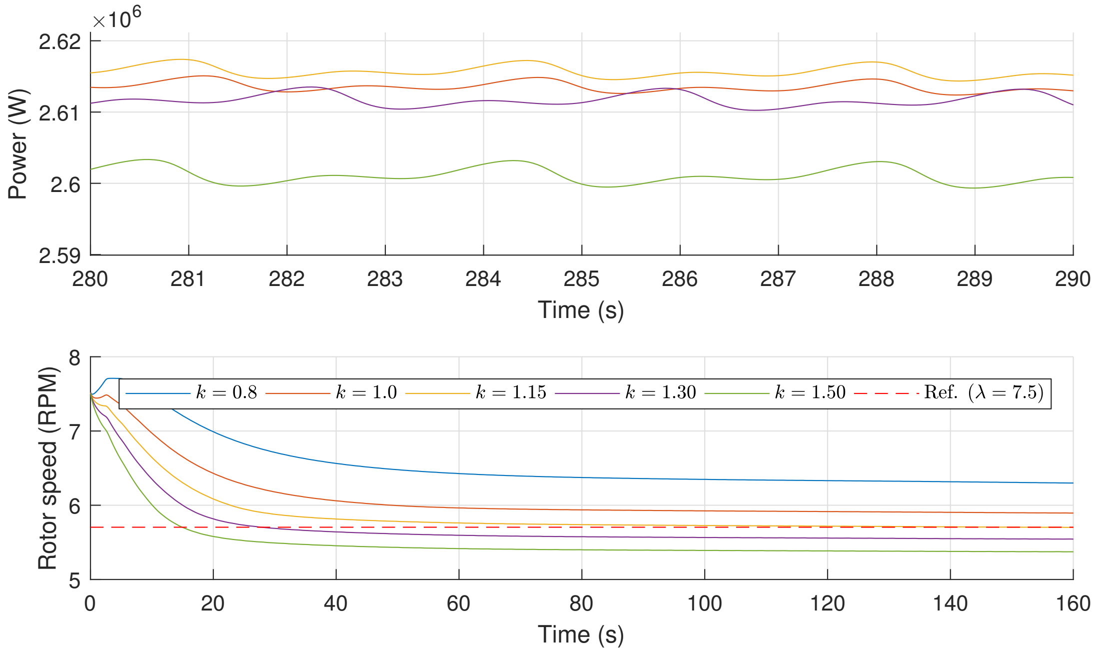

Figure 4. The turbine power capture and the rotor speed for a SOWFA simulation with uniform inflow for various values of k. In these simulations, the FORCESCALAR value is 1.15.

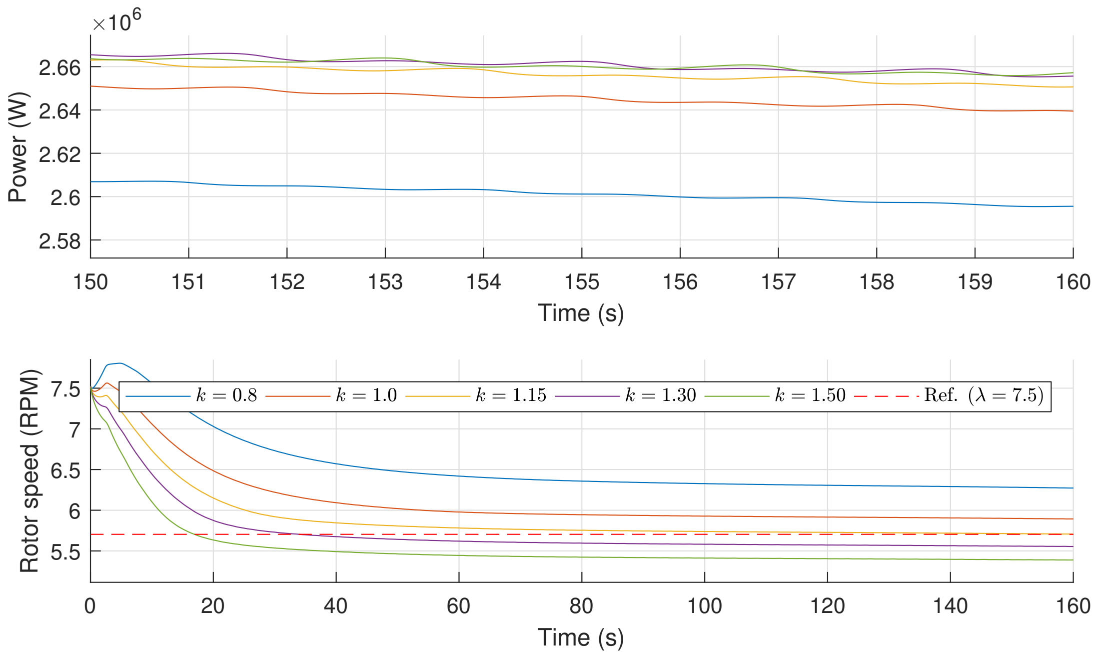

Figure 5. The turbine power capture and the rotor speed for a SOWFA simulation with uniform inflow for various values of k. In these simulations, the FORCESCALAR value is 1.30.

A similar analysis can be performed for the coarser simulation with $\Delta x = 2.5$ m and $\Delta t = 0.20$ s. Fortunately, the optimal FORCESCALAR value and the optimal k-value are consistent across different temporal/spatial resolutions. Thus, also here, FORCESCALAR $= 1.15$, $k = 1.15$, with furthermore $\epsilon = 5.0$ m.

Finally, to validate the thrust generated by the rotor on the flow, the wake profile in SOWFA is compared to what is predicted theoretically using actuator disk theory. The comparison is shown in Fig. 6.

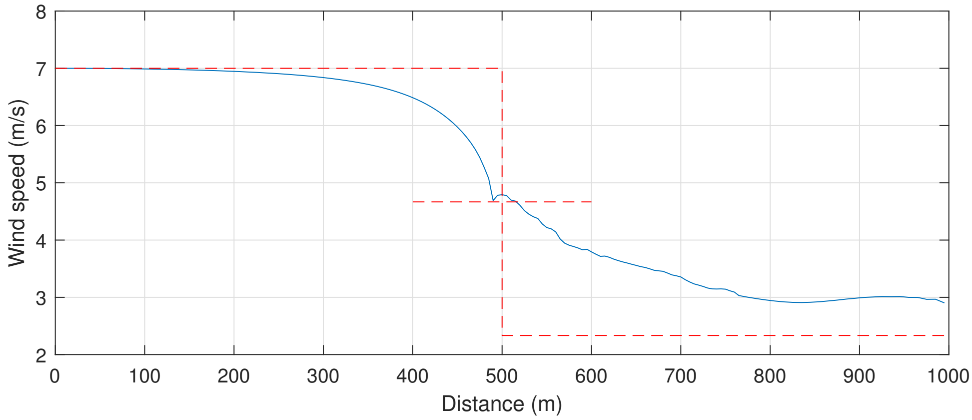

Figure 6. A comparison of the flow profile through the rotor (located at $x = 500$ m) in SOWFA (blue line) with what is predicted in an idealized scenario from actuator disk theory (red dashed line).

Generally, the wind speed is very well described, especially the induction zone in front of the wind turbine. The wind speed at the turbine ($x = 500$ m) matches exactly with what is predicted from actuator disk theory where $U_{\text{rotor}} = \frac{2}{3} U_\infty$. Furthermore, in the far wake, the wake deficit is smaller than what is predicted by actuator disk theory. Actually, this theory focuses on the flow through a turbine. Rather, SOWFA focuses on the complete flow dynamics, thereby including the phenomenon of wake recovery. Furthermore, a number of assumptions such as the rotor being a perfect disk uniformly applying a force on the flow does not hold for the SOWFA simulation. Generally, a satisfactory match is found. Thus, the DTU 10MW turbine has succesfully been implemented in SOWFAs advanced actuator line model ("ALMAdvanced").

The implementation is open-access, available on Github [12].