WFSim validation based on realistic experiment measurement data

WFSim has been widely used in various WF studies. Its accuracy and practical application have been validated previously [1] [2], which have demonstrated that WFSim is able to capture the dominant dynamics of the WF wakes. In this supplementary material, we further validate its simulation capacity with realistic measurement data.

A series of experiments were carried out at the MEL wind tunnel by Garrad Hassan [3]. It the experiments, a 1/160 scaled horizontal axis wind turbine model was tested in a flat terrain with an artificial surface roughness length of 0.075 m. The full-scale rotor diameter is 43.2m and the hub height is 50 m. In these experiments, the free wind speed was set to be 5.3 m/s. Different thrust coefficients of 0.62 and 0.85 were selected for the measurement. Multiple sets of realistic measurement data including lateral wake profiles and centerline velocities profiles were reported in [3]. In this supplementary material, representative data samples for different positions in the wake and different turbine operation conditions and are used to validate WFSim.

The comparison results are shown below. For the case with C_T = 0.62, lateral profiles of normalized wake velocity behind the wind turbine at three downwind locations from the turbine rotor (2.5D, 5D 10D) are measured and shown in Fig. 1, Fig. 2 and Fig. 3, respectively. In the figures, *D* represents the turbine diameter. *r* represents the radial distance from rotor axis. U denotes the wake velocity behind wind turbine, and U_0 is the inflow wind velocity. The simulation parameters for the WFsim are set as follows:

```
'powerscale',0.95,... % Turbine power scaling
'forcescale',2.1 ... % Turbine force scaling
'u_Inf',5.3,... % Initial long. wind speed in m/s
'v_Inf',0.0,... % Initial lat. wind speed in m/s
'lm_slope',0.05,... % 0.067 Mixing length in x-direction (m)
'd_lower',0.6,... % Turbulence model gridding property
'd_upper',1390.9,... % Turbulence model gridding property
'Rho',1.20 ... % Air density
'Lx',1800,... %600 Domain length in x-direction
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'Ly',200,... % Domain length in y-direction

'Nx',300,... % 100 Number of cells in x-direction

'Ny',100 ... % Number of cells in y-direction

As shown in these figures, the results from the simulator agrees well with the realistic measurements. At the location of x = 2.5D, the maximum velocity deficit is about 50% of the incoming velocity, while the value is around 30% for the location of x = 5D, and 15% for the location of x = 10D. Such wake velocity deficits for different downwind locations are modelled accurately by the simulator. Besides, the lateral wake shape is also well captured.

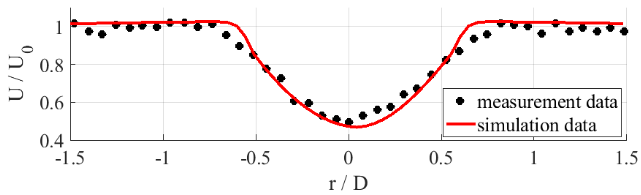

Fig. 1. Lateral profiles of normalized velocity in the wake behind the wind turbine of 2.5D downwind location for $C_T = 0.62$

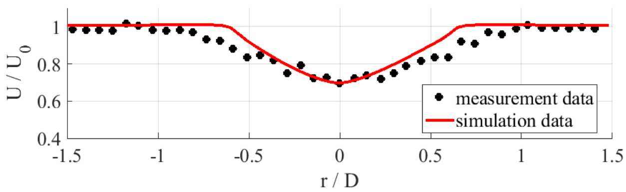

Fig. 2. Lateral profiles of normalized velocity in the wake behind the wind turbine of 5D downwind location for $C_T = 0.62$

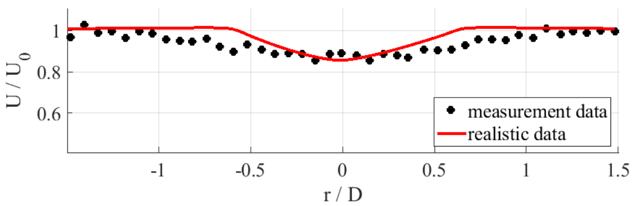

Fig. 3. Lateral profiles of normalized velocity in the wake behind the wind turbine of 10D downwind location for $C_T = 0.62$

Calculations of the velocity along the wake center in the stream-wise direction from simulator and the measured data are shown in Fig. 4.

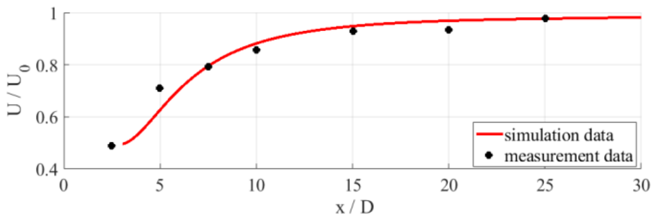

Fig. 4. Normalized wake velocity along the wake center in the stream-wise direction from

the simulation and the measured data for $C_T = 0.62$

For the case with $C_T = 0.85$, the corresponding results of lateral wake profiles are shown in Fig. 5 and Fig. 6. In this scenario, lateral profiles behind the wind turbine at 2.5D and 5D are measured and compared with the simulation results. The velocity along the wake center in the stream-wise direction is compared in Fig. 7. At the location of x = 2.5D, the maximum velocity deficit is about 70%. Because of different turbine operation conditions, the wake effect is more severe at the same location compared to the case with $C_T = 0.62$. Under the same parameter settings, WFSim can accurately capture the influence of different turbine operation conditions on the wake velocity deficit.

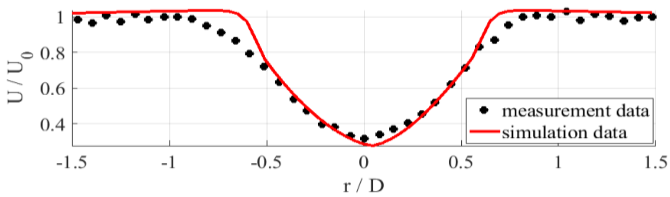

Fig. 5. Lateral profiles of normalized velocity in the wake behind the wind turbine of 2.5D downwind location for $C_T = 0.85$

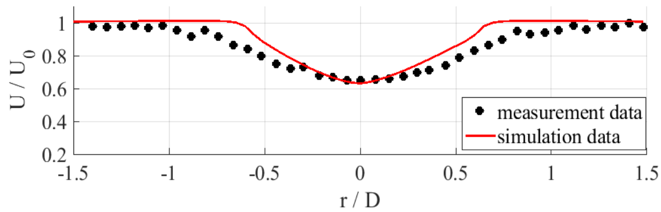

Fig. 6. Lateral profiles of normalized velocity in the wake behind the wind turbine of 5D downwind location for $C_T = 0.85$

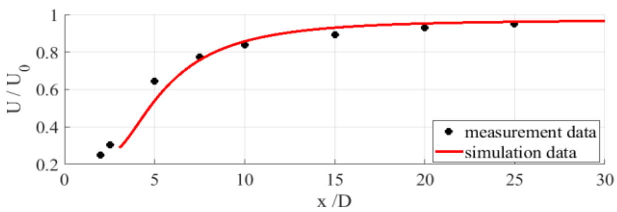

Fig. 7. Normalized wake velocity along the wake center in the stream-wise direction from the simulation and the measured data for $C_T = 0.85$

Under different operation conditions, the simulation results of WFSim is validated against realistic field measurement data. For different positions and turbine operation conditions, the simulation results agree well with the realistic data in both the streamwise and lateral directions. The simulator successfully captures the velocity deficits and wake shape for different wake positions, as well as the influence of turbine operation on the wake effect.

For other validation results, readers are referred to previous studies [1] and [2]. Note that the focus of this paper is the proposition of the deep learning aided MPC framework. Besides, the specific simulation parameter settings do not influence the application of the proposed algorithms. So we do not further analyze the parameters of the wake model which have been thoroughly analyzed in [1] and [2].

[1] S. Boersma, B. Doekemeijer, M. Vali, J. Meyers, J.-W. van Wingerden, A control-oriented dynamic wind farm model: WFSim, Wind Energy Science 3 (1) (2018) 75–95.

[2] M. Vali, V. Petrovi´c, S. Boersma, J.-W. van Wingerden, L. Y. Pao, M. Kühn, Adjoint-based model predictive control for optimal energy extraction in waked wind farms, Control Engineering Practice 84 (2019) 48–62.

[3] Schlez W, Tindal A, Quarton D. GH wind farmer validation report. Garrad Hassan and Partners Ltd, Bristol; 2003.