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An adaptive 3D force distribution model for calculating interactions and power production in an array of vertical axis water turbines

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Summary: A simplified steady state CFD model using force source terms is implemented in OpenFoam to model the power production and the flow in an array of vertical axis tidal turbines. The study explains how to interpolate the force distributions from a set of blade resolved simulations of a whole turbine, depending on the flow striking each turbine of the array.

Introduction

Modeling wind, river or tidal turbine wake interactions between several machines is challenging because the physics in the wake must be modeled with a sufficient accuracy, yet not too much details to keep large array simulations affordable. Simplified CFD models have therefore been developed, using force source terms to represent the action of the turbine on the flow. An example of such model for vertical axis turbines is the Actuator Line model coupled to a LES solver developed by Mendoza et al.[1]. The model takes into account the dynamic stall to obtain the drag and lift curves providing the forces to apply, and gives excellent results. The approach developed here is even more simplified and uses affordable steady state simulations, with a detailed force distribution.

Methods

The simplified model developed in this work uses steady state RANS simulations and represents vertical axis turbines by an average force distribution. This force distribution is obtained beforehand from unsteady blade-resolved simulations of one whole turbine (3D URANS simulations) and it is therefore varying with the azimuth angle. The simplified model uses the k-omega SST turbulence model and has been validated by a comparison to experiments [2]. It proves to give good results for modeling the far wake (further than 4 diameters downstream of the turbine) but poor accuracy in the near wake. This is considered sufficient for modeling turbine arrays, where distances between consecutive turbines are expected to be bigger than this value.

In a turbine array, the forces to impose must be calculated depending on the flow velocity striking each turbine. The local machine velocity, named U_{local}, is obtained with a spatial-averaging of the velocity in all cells of the cylinder swept by the vertical axis turbine, as shown in Figure 1.a. A local advance parameter $\lambda^* = (\Omega R)/U_{local}$ can be defined using this local velocity (with R the radius and Ω the rotational speed of the turbine). The power coefficient curves drawn using the velocity far upstream of the turbine give different results depending on the confinement of the turbine used. It seems that results become independent of the confinement when using the local machine velocity to compute the corresponding power coefficient C_p^* as a function of λ^*. Local force coefficients for each components of force (the thrust coefficient and the equivalent coefficients in the 2 other directions) can be defined in the same way, and also seem to be independent of the confinement used. Although not shown here, this phenomenon is verified by comparing three different confinement cases of blade resolved URANS simulations.

In the adaptative force distribution model, forces added in the momentum equations are calculated at each iteration. The local machine velocity is calculated, then the corresponding forces are interpolated from the force coefficient curves obtained before with a set of blade resolved calculations. The rotational speed of the machine Ω, or a certain value of λ^*, can be chosen to impose the operating point of each turbine depending on the control strategy chosen. After convergence, the power produced by each turbine is calculated with the power coefficient curve depending on the local machine velocity. All those steps are summarized in Figure 1.b.

Results

A configuration of 5 vertical axis turbines placed in a confined channel is tested and presented in Figure 2. The constant λ^* control strategy is used, therefore the turbines rotate at different speeds (see Table 1). To be

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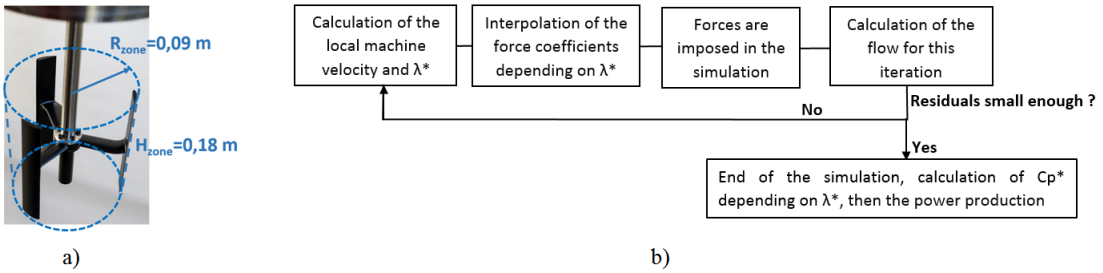


Figure 1: a) Volume used for the local velocity calculation; b) Computation loop of the force distribution model

dimensionless, the output power is divided by the nominal power generated by the same turbine in unconfined conditions, at its point of maximum efficiency. We can see in Table 1 that the power productions of the turbines located on both sides of the first turbine benefit from the acceleration of the fluid created on both sides of its wake. The turbine 1 located approximately 8.5 diameters downstream of turbine 0 witnesses a power reduction, and turbine 4 located too close to turbine 1 (3.5 diameters downstream) has a drastic reduction in power production.

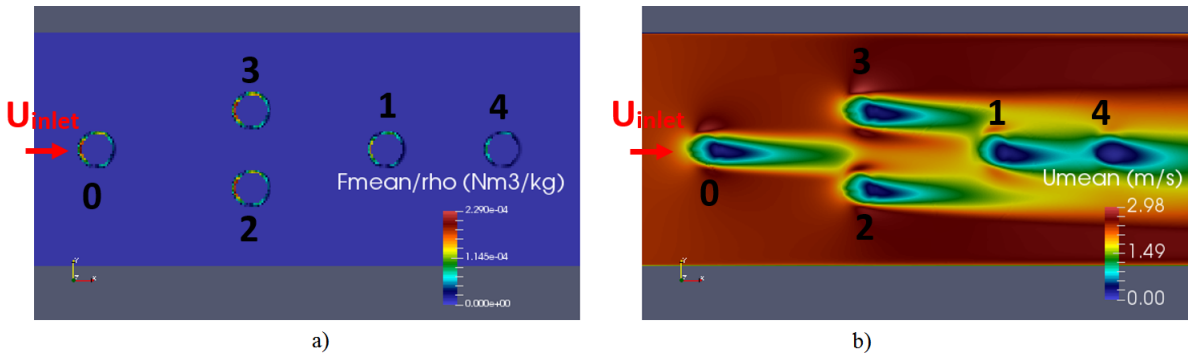


Figure 2: a) Norm of the force distributions; and b) Velocity field; in a horizontal plane crossing the turbine blades

Turbine number	0	1	2	3	4
P/P_n	0.97	0.60	1.10	1.11	0.23
λ^*	3.51	3.51	3.51	3.51	3.51
Ω (rad/s)	47.5	40.4	49.5	49.8	29.5

Table 1: Operating values Ω and λ^*, and dimensionless power production of each turbine

Conclusions

Promising results are obtained using the presented method to adapt the force distribution to the local velocity of each turbine, and the behavior of turbines in an array is reproduced correctly. The convergence loop proves to be stable even for unfavorable cases with a turbine placed in the near-wake of another one. Results are however qualitative and different settings (mesh convergence, etc...) or configurations still need to be tested.

Acknowledgments:
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