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# Blade–wake interactions in cross-flow turbines

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ABSTRACT

This paper presents analytical bounds for blade–wake interaction phenomenona occurring in rotating cross-flow turbines for wind and tidal energy generation (e.g. H-rotors, Darrieus or vertical axis). Limiting cases are derived for one bladed turbines and extended to the more common three bladed configuration. Additionally, we present a classification of the blade–wake type of interactions in terms of limiting tip speed ratios.

These bounds are validated using a high order $h/p$ Discontinuous Galerkin solver with sliding meshes. This computational method enables highly accurate flow solutions and shows that the analytical bounds correspond to limiting blade–wake interactions in fully resolved flow simulations.

## 1. Introduction

Rotating airfoils on a fluid present a challenging problem since fluid–structure interactions are likely to occur. Examples where airfoil rotation may lead to fluid–structure interactions can be found in turbomachinery applications, helicopter aerodynamics, insect flight aerodynamics, unmanned air vehicles and flows through renewable energy devices such as wind and tidal turbines.

The effect of vortices interacting with blades and airfoils have been summarised in the past [26,6]. These effects vary from mild vibrations to unsteady loading that may result in structural fatigue and potential failure. In addition, vortex interactions often result in uncontrolled sound generation. In summary, blade vortex interactions result in non-linear processes that are difficult to control and whose effects are generally damaging in terms of aerodynamics, structural integrity and acoustics.

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Prediction of the conditions that lead to such interactions are therefore of capital importance for engineering applications since they define the design envelope and influence the structural integrity of the device. Furthermore, these interactions restrict the use of simplified analytical tools or semi-empirical correlations.

Cross-flow wind and tidal turbines for power generation, also known as H-rotors, Darrieus or vertical axis turbines, present interesting interactions and complex flow phenomena. These type of turbines consist of foil shaped blades that generate lift forces so as to rotate a shaft to which the blades are connected. Therefore azimuthal changes in blade aerodynamics (or hydrodynamics if tidal devices are considered) are common, resulting in complex flow phenomena such as stalled flows, vortex shedding and blade–vortex interactions. The interested reader is referred to [18,8,33,21] for cross-flow turbines in the context of wind power generation and to [23] for its use in urban environments. Tidal turbines have become increasingly popular and their particularities can be found in [34,15,7,1].

Various engineering techniques have been developed to model flows through cross-flow turbines, but these may prove inadequate in capturing some complex flow phenomena (see [18] for a review). In particular, blade–vortex interactions are often neglected in simplified analysis codes (e.g. actuator disc or Blade Element Momentum) and hence the limits for which these solvers are accurate remain unclear. For example, popular methods for turbine applications, that can benefit from our analysis, are *lifting line* or *vortex models* methods, e.g. [18,30]. These rely on pre-existing lift and drag data to model the blade aerodynamics and allow for free development of wake structures and their evolution. However, if blade–vortex interactions occur, then *vortex models* are unable to naturally account for modifications of the lift and drag data due to the vortex impingement on the blades. Without modifying the aerodynamic coefficients, these models are unlikely to predict accurately the turbine aerodynamics. Our analysis can predetermine the range of usability of such models or even determine if corrections are needed in the lift and drag input data.

Previous works have studied wake and vortex interaction effects for particular geometries using complex numerical methods (e.g. [29,28]) but have not attempted to derive generalised analytical estimates to bound blade–wake interactions.

Our work analyses the physics involved in cross-flow turbines to derive bounds on blade–wake interactions in terms of geometrical factors (i.e. tip speed ratio). To the authors' knowledge, these analytical estimates are a first attempt to bound the various types of blade–wake interactions that may be used in the future to correct simplified models of blade element momentum type. The analytical bounds included in this paper may provide limiting conditions for analytical or algebraic models (e.g. [24,32,35,31] for cross-flow wind turbines or [34,15,7] in the tidal energy context) and also improve the understanding on the behaviour of turbine's starting conditions (e.g. [27,14]).

To validate the analysis, we present fully resolved numerical simulations of cross-flow turbines and compare the derived analytical bounds to numerical results for one and three bladed turbines. Numerous studies have computed vertical axis turbines using low order methods (e.g. [20,16,25,3,17,2,22]) but to the authors' knowledge there has not been any previous attempts to compute rotating turbines using a high order solver with sliding meshes [13,10]. The solver accuracy does not degrade when the mesh is dynamically moved and hence is well suited for the study of fluid–structure interaction phenomena [13].

The main contributions of our work can be summarised in the following bullet points:

- We present novel analytical bounds for blade–wake interaction phenomena occurring in rotating cross-flow turbines.
- We characterise the blade–wake types of interactions for one and three bladed turbines.
- We validate these analytical bounds and associated flow regimes using a high order Discontinuous Galerkin solver with sliding meshes.
- We provide novel result for rotating airfoils that may be used in the future for numerical validations.

The paper is organised as follows. First, we introduce the analytical bounds for one and three bladed turbines. Second, we compare these estimates with numerical simulations to validate our analytical bounds.