1 Introduction

The current paper aims to describe the state-of-the art on far-wake aerodynamics and engineering models related to wind turbines in yaw. Wind turbine yaw involves a state whereby the rotor is not exactly facing the inflow, a condition occurring due to the wayward nature of the turbulent wind [5]. Consequently, the rotor is subject to a lower power output and increased fatigue loading. For this reason, the rotor and near-wake aerodynamics have frequently been studied (e.g. [8, 12, 14]), see also the review by Micallef and Sant [13].

Quite recently, the property of yaw has come under the attention for a whole different reason. Conventionally, a wind turbine sheds a straight wake as a product of the energy conversion process, which is characterized by a lower wind speed and increased turbulence levels. If turbines are grouped in wind farms, power losses will emerge, as these wakes will interfere with neighbouring turbines. Typical examples of wake losses are an estimated 12% and 23% decrease in power output for the Horns Rev and Lillgrund wind farms respectively [1]. If a turbine is put in yaw, also a cross-component of thrust is exerted on the wind, which makes the wake deflect sideways. It has been demonstrated by numerical simulations [6], and experiments in the wind tunnel [4] and field [7], that putting turbines deliberately in yaw can increase the power output of wind farms significantly by literally steering wakes around neighbouring turbines.

Whereas the rotor and near-wake aerodynamics have properly been addressed, designing engineering models for wake steering also requires a thorough understanding of the wake further downstream of the rotor. From a yaw controls perspective, literature surveys have been provided by Knudsen et al. [10] and Boersma et al. [3], but they did not examine the far-wake aerodynamics in detail. Due to the lack of fundamental understanding, current engineering models are based on simple axi-symmetrical assumptions and theories developed through years of experience with studying the wakes of turbines under normal operations, while it has been demonstrated that deflected wakes are inherently asymmetrical by nature [2, 9, 11] for which the validity of conventional assumptions is only limited.

To bridge this gap, a survey is carried out with a two-fold objective. First, an overview is provided of relevant studies to shape the current understanding of skewed far-wake aerodynamics aft of wind turbines in yaw. Due to the physical similarity, this study also involves literature on cross-flow jets and helicopters in forward flight. Second, an overview an inter-comparison is made of related engineering models, whereby it is identified whether these models are capable of sufficiently describing the wake in yaw. Included are kinematic, field, and vortex models.

The paper is structured as follows. In section 2, a brief overview of rotor aerodynamics is given, as the yawed rotor is at the origin of the skewed wake. Section 3 continues with a thorough review of numerical and experimental studies on the skewed wake itself. Focus is on understanding the three-dimensional convective and turbulent flow properties. In section 4, all known engineering models are outlined, which is followed by a mutual comparison in section 5, where it is assessed to what extent these models are able to predict the relevant wake physics. Finally, section 6 provides a conclusion of the current state-of-the art and gaps in research.

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