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Aerodynamic wind-turbine rotor design using surrogate modeling and three-dimensional viscous–inviscid interaction technique

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ABSTRACT

In this paper a surrogate optimization methodology using a three-dimensional viscous-inviscid interaction code for the aerodynamic design of wind-turbine rotors is presented. The framework presents a unique approach because it does not require the commonly-used blade element momentum (BEM) method. The three-dimensional viscous-inviscid interaction code used here is the accurate and fast MIRAS code developed at the Technical University of Denmark. In comparison with BEM, MIRAS is a higher-fidelity aerodynamic tool and thus more computationally expensive as well. Designing a rotor using MIRAS instead of an inexpensive BEM code represents a challenge, which is resolved by using the proposed surrogate-based approach. As a verification case, the methodology is applied to design a model wind-turbine rotor and is compared in detail with the one designed with BEM. Results demonstrate that nearly identical aerodynamic performance can be achieved using the new design method and that the methodology is effective for the aerodynamic design of wind-turbine rotors.

1. Introduction

Wind-turbine blade design involves many disciplines in engineering and several methods have been proposed to determine optimum designs. For blade aerodynamic design, methods range from simplistic methods using analytical expressions, see e.g. Refs. [1,2], to sophisticated optimization problems that incorporate other disciplines in the design process [3,4]. The majority of blade design problems in the literature implement the blade element momentum (BEM) method, while others use vortex-based [5,6] or computational fluid dynamics (CFD) methods [7].

To mitigate the computational time of wind-turbine design problems, researchers have used surrogate models, e.g. response surface models (RSMs), Kriging and artificial neural networks (ANNs). Lee et al. [8] used RSM to reduce the calculation time of a complex two-step multi-objective optimization problem for blade design. RSMs were particularly useful in Refs. [9] and [10], where expensive numerical computations of the Navier–Stokes equations were used to design wind-turbine airfoil profiles. Similarly, Han et al. [11] designed wind-turbine airfoils using CFD, but Kriging was preferable as the surrogate model. ANN was used as the surrogate model together with CFD in Ref. [12] to design wind-turbine airfoils as well.

This paper describes an initial effort to mitigate the computational time when using surrogate optimization with viscous-inviscid interaction (VII) tool for wind-turbine rotor design. The aerodynamic tool used in the present work is the three-dimensional (3D) Method for Interactive Rotor Aerodynamic Simulations. The verification design case described in the present paper concerns only a simplified small wind-turbine rotor model using steady and uniform wind. In the future, the optimization method will be applied and tested for large wind-turbine blade design with fluid–structure interaction.

The paper is organized as follows: Section 2 describes the MIRAS code and the surrogate-optimization method, Section 3 describes the basic properties of the model rotor and its design using the inverse-design and surrogate-optimization methodologies, and finally Section 4 gives the conclusions.

2. Design method

In this section, we describe the methodology used for the aerodynamic design of wind-turbine rotors. It comprises the subsections Q^3UIC, MIRAS and surrogate modeling for optimization.

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Nomenclature

α	angle of attack
$\boldsymbol{\psi}$	vector of basis functions, ψ
$\mathbf{w}$	vector of weight coefficients, w
$\mathbf{x}$	vector of design variables, x
μ	dynamic viscosity of air
ω	rotational/generator speed
ρ	density of air
dC_P	local power coefficient
X_{design}	design point of parameter X
$\hat{f}$	surrogate approximation of f
B	number of blades
c	chord length
C_d	drag coefficient
C_l	lift coefficient
C_P	power coefficient
$C_{P,fit}$	power coefficient for best-fit baseline shape
f	scalar-valued objective function
L	lower boundary constraint
l	local aspect ratio, c/r
n	number of variables
R	rotor radius
r	radial position of the rotor or span-wise blade position
R_O	rotational number, $\omega r/U_{rel}$
r^2_{coe}	correlation coefficient
R_{hub}	hub radius
Re	Reynolds number, $\rho U_{rel} c/\mu$
U	upper boundary constraint
U_o	design wind speed
U_{rel}	relative wind speed
X	number of grid points along each variable dimension
2D	two-dimensional
3D	three-dimensional
ANN	artificial neural network
BEM	blade element momentum
CFD	computational fluid dynamics
CP	control point
LHS	latin hypercube sampling
MIRAS	method for interactive rotor aerodynamic simulations
NRMSE	normalized root mean squared error
Q^3UIC	quasi-3D unsteady viscous-inviscid interactive code
RPM	revolutions per minute
RSM	response surface model
VII	viscous–inviscid interaction

Note that Q^3UIC is considered as an integral part of MIRAS. The methodology and theory used in both Q^3UIC and MIRAS is extensive and will only be briefly described. For full comprehension, the reader is referred to [13] and [14].

2.1. Q^3UIC

Q^3UIC [13] is a two-dimensional (2D) and quasi-3D, steady and unsteady, VII code used for simulating the aerodynamic behavior of airfoils. Q^3UIC is a stand-alone code integral to MIRAS and is described first because Q^3UIC is a pre-processor to MIRAS. MIRAS is described in Subsection 2.2 and the MIRAS input data from Q^3UIC is explained in Subsection 2.2.1.

Q^3UIC consists of two parts: 1) the inviscid part, modeled by a 2D panel method following Hess [15] and 2) the viscous part, governed by the integral form of the boundary layer equations with capability of solving laminar as well as turbulent flows, including laminar to turbulent transition prediction. The viscous part is modeled in the boundary layer region surrounding the airfoil surface, while the flow outside is assumed inviscid, and can be modeled using potential flow theory. The boundary layer equations are extended to include 3D rotational effects, which gives Q^3UIC a quasi-3D capability.

The equations governing the VII technique represent a

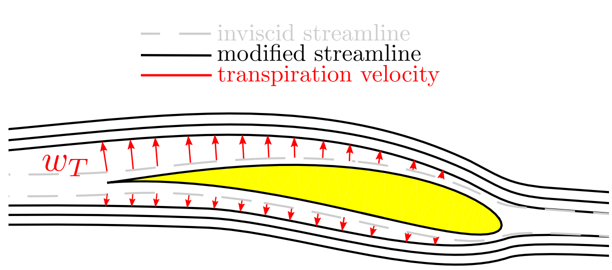

Fig. 1. Transpiration velocity concept in Q^3UIC shown for an airfoil.

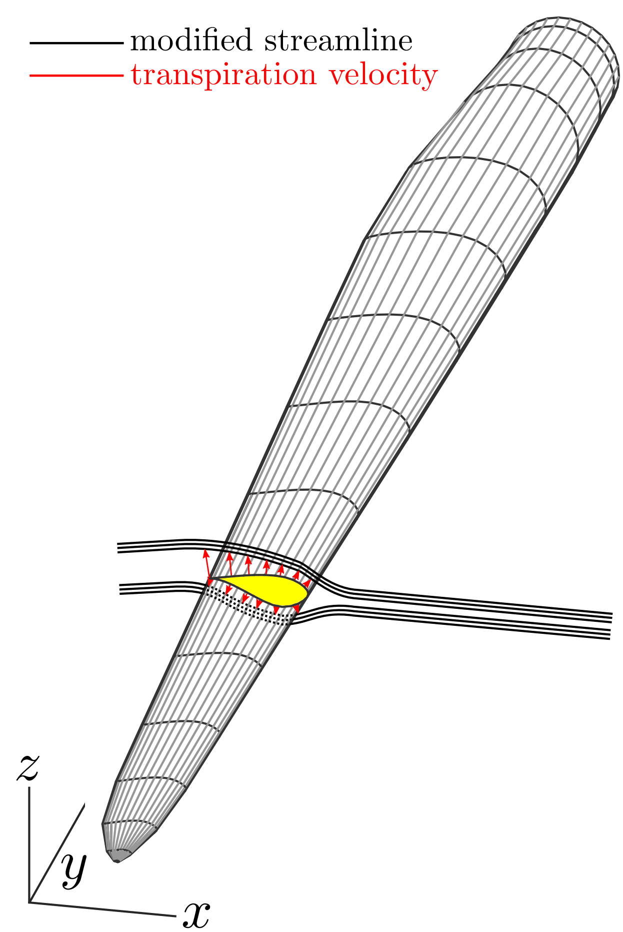

Fig. 2. Three-dimensional panel method shown for a wind-turbine blade in MIRAS where the inviscid streamlines for one station is modified using the transpiration velocity from Q^3UIC.