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ROBUST DESIGN OPTIMIZATION OF WIND TURBINE ROTORS

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ABSTRACT

Wind turbine design is an inherently multidisciplinary task typically aiming at reducing wind cost of energy. In many cases the fulfillment of all design specifications and constraints is still accomplished using an iterative trial and error-based strategy. This may hinder the exploration of the feasible design space, lead to suboptimal solutions, and prevent the assessment of new and promising configurations. These shortfalls can be removed by using numerical optimization to optimize in an automated fashion wind turbine design. An additional challenge to turbine design arises from sources of uncertainty affecting wind turbine operation (e.g. wind variability), manufacturing, assembly and control (e.g. finite manufacturing tolerances and control system perturbations and faults), and the design process itself (e.g. uncertain accuracy of design tools). By adopting uncertainty quantification and propagation methods in the automated design process, the deterministic optimization becomes a probabilistic or robust design optimization process. This yields machines whose performance has reduced sensitivity to the abovesaid stochastic factors. The paper summarizes recent research work by the author and his group in the robust design optimization of horizontal axis wind turbine rotors, and it highlights some crucial areas of future research.

Keywords: wind turbine multidisciplinary design, computational aerodynamics, robust optimization

NOMENCLATURE

C_L	$[-]$	lift coefficient
N	$[rpm]$	rotational speed
P_e	$[kW]$	electrical power
U	$[m/s]$	wind speed
AEP	$[kWh]$	annual energy production
BM	$[kNm]$	bending moment
LCOE	$[\$/kWh]$	levelized cost of energy
PDF	$[-]$	probability distribution function
r	$[m]$	radial position
$x/c, y/c$	$[-]$	airfoil coordinates nondimensionalized by chord c
α	$[deg]$	angle of attack

1. INTRODUCTION

In recent years the exploitation of wind energy for producing electricity has been rapidly growing worldwide. This has been partly enabled by recent design technology advances, which have made possible substantial reductions of wind cost of energy (COE), one of the main metrics used to assess the viability of energy sources. The most widespread turbine type for heavy-duty on-shore and offshore installations is the horizontal axis wind turbine (HAWT). HAWT design, which typically aims at minimizing COE, is an inherently multidisciplinary task requiring the achievement of design specifications and the fulfillment of conflicting constraints dictated by aerodynamics, material engineering, structure mechanics and aeroelasticity, control, electrical and power engineering, and economic requirements. The characteristics of HAWT rotors, here intended as the set of turbine blades and the conversion control system from wind to mechanical power entering the drivetrain, play a major role in the design of the entire turbine, as they determine the steady and time-dependent structural loads on drivetrain, tower and foundations, and also the electrical power characteristics required for designing the power electronics subsystems. The main blade characteristics are their number, size, outer shape, internal geometry and material, while options available for power control include *a*) passive stall regulation for smaller HAWTs, and *b*) variable speed pitch-to-feather control for multimegawatt turbines.

The design of the rotor [1] as well as that of the entire turbine [2] is usually carried out using an iterative trial and error-based strategy. In rotor design, one starts by defining the outer blade shape, and this is followed by the definition of the internal structure which is modified in subsequent structural and aeroelastic analysis if found inadequate to withstand the aerodynamic loads. The iterative process may also yield the redefinition of the outer blade shape. One of the drawbacks of the manual iterative approach is the likelihood of incomplete exploration of the feasible design space, which may result in suboptimal solutions and prevent the scrutiny of radically new, potentially better configurations. A fully automated multidisciplinary design optimization (MDO) approach based on numerical optimization can avoid these pitfalls and yield substantial improvements of HAWT configurations.

In the area of turbine design Fuglsang *et al.* [3] developed a gradient-based HAWT MDO system to minimize COE, and used it to optimize the turbine design for site-dependent wind conditions. They showed that optimized site-specific designs achieved COE reductions of up to 15 % through annual energy production (AEP) increments and manufacturing cost reductions. Maki *et al.* [4] optimized the design of a 3-blade 1 MW HAWT using a multilevel system design to minimize COE. Their optimized configuration featured a reduction of about 29 % of COE, had higher rated rotational speed, larger diameter and lower rated power than the reference HAWT configuration. Their results also highlighted that COE had a minimum with respect to the rotor diameter and the rated rotational speed, and increased monotonically with the rated power. Ashuri *et al.* [5] used a gradient based optimizer to optimize the design of the National Renewable Energy (NREL) 5 MW virtual HAWT [6], reporting a 2.3 % COE reduction.

HAWT design and operation are affected by significant uncertainty caused by environmental, aerodynamic and engineering factors. Accounting for stochastic factors in the design optimization process yields a robust MDO (RMDO) process [7], whereby the deterministic estimates of objective functions and constraints are replaced by probabilistic estimates. Unlike deterministic designs, robust designs feature reduced performance sensitivity to stochastic variations of operation, control and engineering factors. RMDO is computationally more expensive than MDO because at each RMDO step multiple analyses of the same nominal design are required for propagating uncertainty [8] in the multidisciplinary analysis system. The recent development of numerically efficient uncertainty propagation methods [9] and the high performance of modern computers are making the computational burden of RMDO affordable.

HAWT RMDO is a very recent but extremely promising technology that can subsantially improve HAWT design and on which only a few advanced studies are available [10, 11, 12, 13] to date. This paper presents the research work carried out in this area by the author and his group. The options available for the modules of the multidisciplinary HAWT rotor analysis system are discussed in Section 2. Section 3 discusses the choice of methods for propagating uncertainty in the multidisciplinary analysis system, defines the objectives and constraints of HAWT rotor RMDO problem, and available approaches to its solution. Two sample applications of HAWT RMDO are presented in Section 4, while a summary with ongoing and future research trends is provided in Section 5.

2. MULTIDISCIPLINARY ANALYSIS

HAWT rotor MDO and RMDO rely on integrated multidisciplinary analysis (MDA) systems, made up of interlinked modules. For given rotor diameter and hub height, parameters defining the outer shape of the blades and their internal structure, power regulation, and wind parameters from cut-in to cut-out speeds, the MDA system returns the output required for the design optimization, such as AEP, COE, structural stresses and fatigue damage. MDA systems typically include: *a*) parametrized models of the blade outer and inner shapes, *b*) an aerodynamic module to determine the rotor power and the aerodynamic loads acting on the blades, *c*) an aero-servo-elastic subsystem for determining the aeroelastic characteristics of the rotor, and, in some cases, also the effects of blade deformations on power generation, *d*) a stress analysis module to determine the design-driving stresses of the blades subject to aerodynamic, weight and centrifugal loads.

2.1. Geometry parametrization

Both the outer shape of the blades and their internal structure need to be defined by suitable parametric representations. The input variables on which such parametrizations depend are the design variables.

As for the outer blade shape, most studies published in the last two decades parametrize and vary only the radial profiles of blade twist and airfoil chords during the optimization (a few design variables are associated to chord and twist at some radial positions, and cubic splines are used to define the complete radial profile of these two variables), while the blade airfoils are left unaltered [14, 15]. The adopted airfoils are chosen from among custom tailored HAWT or aircraft wing airfoil families for which reasonably reliable (usually experimentally measured) aerodynamic force data are available. As highlighted by Fuglsang *et al.* [16] and further discussed below, the reason for not parametrizing (and thus not designing) the blade airfoils within HAWT rotor design optimization is the difficulty in computing reliable estimates of abovesaid aerodynamic forces for the feasible arbitrary airfoil shapes generated when enabling airfoil geometry variations during the optimization. The same authors also recognized that significant improvements in HAWT design optimization can be achieved by enabling airfoil geometry variations in the optimization. In the light of the potential of new Computational Fluid Dynamics (CFD) to accurately predict transitional and stalled airfoil aerodynamics, new optimization studies start incorporating airfoil design in the 3D rotor design optimization [17, 12, 18, 19].

The airfoil geometry parametrization is often based on composite Bezier curves [12, 19], or even PARSEC parametrizations [17]. The author's group have used a composite 4-Bezier curve parametrization [13], sketched in Fig. 1. The composite parametrization features 14 control points, but the design variables are only 12 abscissas and ordinates of the 14 base points, since the remaining 16 abscissas are determined by fixing the position of the leading and trailing edges, and imposing suitable continuity conditions at the junctions between the 4 component curves.

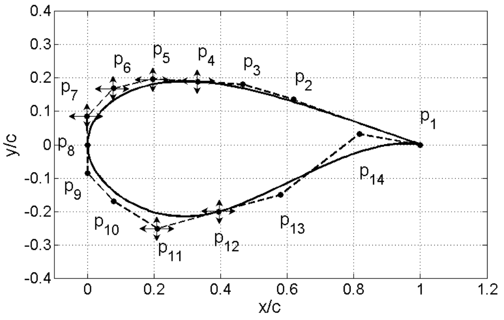

Figure 1. HAWT rotor airfoil parametrization based on composite Bezier curve.

The internal structure of HAWT blades typically consists of spar caps, spar webs and skin elements. Different levels of detail and approximation have been used in HAWT design optimization. Some studies model only the spar caps as they base the structural design on the bending load withstood by such components [14], whereas other studies model the complete internal structure, and use a shell element approach for calculating the stress field [20]. An important feature in HAWT rotor MDO is that the structural model used for the stress and the aeroelastic analyses (the aim of the latter is to determine deformations rather than stresses) are often different. More specifically, the structural model of the stress analysis often includes the 2D geometry of the blade sections, whereas the model of the aeroelastic analysis usually consists only of the radial distribution of section-averaged blade structural properties.

2.2. Aerodynamics

To compute the power generated by the rotor and the aerodynamic loads acting on its blades, a computational aerodynamics module is required. In HAWT rotor MDO and, even more, RMDO, computational speed is a crucial requirement. The blade-element momentum (BEM) theory [21] fulfills this requirement and is therefore widely used in wind turbine design. The BEM model combines the conservation of linear and angular momentum and classical lift and drag theory. Its main limitation is that the reliability of its assumptions and engineering models are questionable in many realistic HAWT rotor flows. Moreover BEM codes require knowledge of the lift and drag coefficients of the blade airfoils. Thus the accuracy of BEM analyses also depends on the source type of airfoil force coefficients.

In the automated RMDO environment, many airfoil geometries are scrutinized and their polars need to be determined very rapidly. In most cases, the viscous-inviscid panel code XFOIL [22] is used. In this code, laminar-to-turbulent transition, an important feature in HAWT rotor aerodynamics, is modeled with the e^N method. XFOIL enables the rapid calculation of the airfoil performance; the code, however, is known to usually overestimate the maximum lift coefficient [23], and is not meant to be used for reliable predictions of the force coefficients beyond the stall inception point. The near stall predictions of XFOIL appear to be particularly inaccurate for thicker airfoils [24]. Improved near-stall force predictions could be obtained with the proprietary code RFOIL, the variant of XFOIL developed at Delft University [23], or even using transitional Navier-Stokes (NS) CFD, which is reaching a level of maturity enabling it to accurately predict airfoil aerodynamics well beyond the angle of attack (AoA) of maximum lift [25]. At present, run-times of NS CFD, even in 2D simulations, are still excessive for their use in HAWT RMDO requiring hundreds or thousands of rotor analyses, but new highly-efficient computer processor architectures are enabling substantial run-time reductions of NS CFD for wind turbine analysis and design [26]. This is expected to accelerate the use of these technologies for wind turbine design.

In BEM models, the input 2D aerodynamic data are also corrected to account for the complex 3D flow physics of rotating blades, such as the Himmelskampf effect or centrifugal pumping effect [27]. Based on empirically derived equations, models like AERODAS [28] provide a method for calculating stall and post-stall lift and drag characteristics of rotating airfoils, using as input a limited amount of prestall 2D aerodynamic data (e.g. zero-lift AoA, AoA at maximum lift and drag, values of maximum lift and drag coefficients, slope of the linear part of the lift curve, and minimum drag coefficient). Other emprical corrections used in BEM codes include: *a*) Prandtl's tip and hub loss corrections [21], *b*) Glauert-type correction of the curve induction coefficient/thrust coefficient to account for the turbulent windmill state [29].

2.3. Aero-servo-elasticity and structural mechanics

Another functionality set of HAWT rotor MDA systems includes the determination of *a*) blade pitch angle and rotor angular speed (for pitch- and speed-regulated turbines), *b*) all time-dependent blade loads and deflections, *c*) generated power, and *d*) structural stress for each wind regime. The module or collection of interlinked modules implementing the first three functionalities forms the aero-servo-elastic analysis subsystem. Several choices are possible for this subsystem and the stress analysis module, depending primarily on the level of detail of the adopted model. The aero-servo-elastic subsystem used by the author's group is based on the NREL code FAST [30]. For given steady or time-dependent wind conditions, FAST models the aeroelastic behavior of the rotor using a modal representation of the blade displacements and velocities (the code can even model the entire turbine, including drivetrain and tower). In FAST, rotor aerodynamics is analyzed with AERODYN [30], a library implementing the BEM theory. For rotor analyses, the input of the code includes the aerodynamic force coefficients required by AERODYN to determine the aerodynamic loads, the mode-shapes and the radial distribution of the structural properties of the blades. The blade mode-shapes are determined with BMODES [30], a finite element code for calculating the mode-shapes of beams. For HAWT blades, the input of BMODES includes the radial profiles of the distributed structural and geometric properties of the blades and the rotor speed. The radial profile of blade structural properties used by FAST is determined with CO-BLADE [31], a structural analysis code custom-tailored for wind turbine blades. The input of CO-BLADE includes the detailed definition of the blade outer shape and internal structure. The latter includes the number and the orientation of the plies making up the laminates of spar caps, spar webs and skin. CO-BLADE also determines the 3D stress field in the blades using the aerodynamic loads of FAST/AERODYN, and the loads associated with the weight and the centrifugal forces of the blades. These stresses are required for sizing all structural components of the blades. The aero-servo-elastic and stress analysis framework described herein is that used for the RMDO of the 5 MW HAWT discussed in section 4.

3. UNCERTAINTY PROPAGATION AND HAWT RMDO

In HAWT RMDO, part of the design variables (e.g. rotor geometry characteristics) and/or design parameters (e.g. site- and time-dependent wind characteristics) are stochastic. Thus the turbine performance is no longer defined by deterministic but rather by probabilistic metric estimates. A numerical method for propagating the uncertainty affecting the input data is thus required. The two essential prerequisites of uncertainty propagation methods for RMDO are high execution speed and accuracy. These two requirements are conflicting, and case-dependent choices have to be made. When the underlying MDA systems feature low-levels of nonlinearity, first or second order moment methods based on truncated Taylor series [9] yield sufficiently accurate estimates of the statistical moments of the output of interest at low computational costs. For MDA systems featuring strong nonlinearities, conversely, computationally expensive Monte Carlo methods are often the only route to accurate estimates of the output functionals. The univariate reduced quadrature (URQ) method [9] yields an acceptable compromise between cost and accuracy.

The level and type of nonlinearity of the MDA system may be such that mean and standard deviation of the probability distribution function (PDF) of the output are insufficient to characterize the output PDF. This is illustrated in Fig. 2, taken from [11]. The two AEP PDFs of a small HAWT rotor refer to feasible turbines. However, one rotor has a nearly normal AEP PDF (left), whereas the other has a strongly skewed AEP PDF (right). In this circumstance, knowledge of the mean and standard deviation alone may lead to incorrect design choices, and more complex representations of the output PDF in the RMDO context should be used.

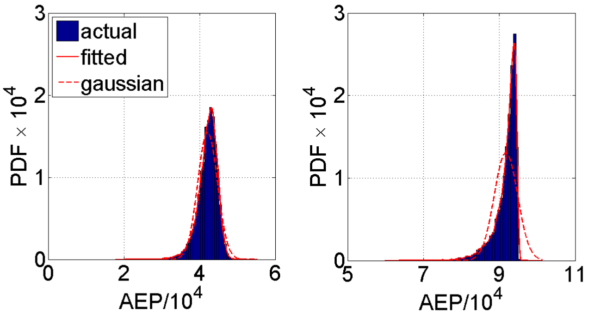

Figure 2. Encountered AEP [kWh] PDFs. Left: quasi-normal output. Right: non-normal output.

The most widely used objective function in HAWT and HAWT rotor MDO is the levelized cost of energy (LCOE) [16, 5, 13]. This variable is the ratio of the sum of all fixed (e.g. turbine and installation) and variable (e.g. operation and maintenance and land lease) costs, and the amount of energy generated over the turbine lifetime. All costs appearing in the definition are net present values. An interesting alternative to optimizing only LCOE is to optimize concurrently both the cost of energy and the annual energy production per unit area [14]. This formulation is particularly interesting when performing HAWT design optimization in the context of wind farm planning.

Structural, aeroelastic and aeroacoustic constraints are used in HAWT rotor design. Wind turbines must meet a large number of requirements for certification, which are coded by the International Electrotechnical Commission (IEC). Many recent HAWT rotor MDO studies derive their constraints from the IEC standards. Examples of structural and aeroelastic contraints include: *a*) maximum stress should not exceed material-dependent limits when the rotor is exposed to strongest foreseen wind in 20 or 50 years (depending on turbine specifications), *b*) maximum blade tip deflection should result in reduction of the blade tip/tower clearance not larger than specified values to avoid tower/blade interference, *c*) all components should achieve the target life of about 20 years despite all fatigue-inducing loads such as wind turbulence and blade weight. Aeroacoustic constraints often result in an upper limit for the rotor speed and some geometry constraints on the outer blade geometry.

Both gradient-based [16, 5, 19] and evolution-based [14, 18] optimizers are used for HAWT MDO. Gradient-based methods are faster but they have more limited capabilities of exploring the feasible design space. Evolution-based algorithms, conversely, require many more evaluations of the objective functions, but they can determine global optima. Moreover, they can also handle discontinuos functions.

Moving from MDO to RMDO, each objective function is estimated probabilistically. One simple approach is to replace the deterministic value of the output with its mean and standard deviation. Then one has to optimize the mean (minimize LCOE, maximize AEP), and minimize the standard deviation. Possible approaches to solving the probabilistic problem include *a*) solving a two-objective optimization, *b*) solving a one-objective optimization where a weighted sum of mean and standard deviation is optimized and *c*) solving a one-objective optimization where the mean is optimized and the standard deviation is a minimum inequality constraint. Using evolution-based optimizers in HAWT RMDO can yield a large computational burden because each probabilistic evaluation of a nominal design can require several deterministic evaluations and a very large number of nominal designs is scrutinized. Making use of sufficient computational resources and using uncertainty propagation methods requiring a small number of deterministic analyses for each probabilistic estimate, however, make the use of evolution-based optimizers viable also for HAWT rotor RMDO [11].

4. SAMPLE APPLICATIONS

4.1. AEP optimization of small HAWT rotor

The objective of this prototype HAWT rotor robust design optimization was to optimize the AEP of a 3-blade 12.6 meter-diameter speed-regulated rotor from cut-in to rated wind speed. The yearly frequency distribution of the freestream wind velocity U is taken to be a Weibull PDF with scale parameter of 7 m/s and shape parameter of 2, resulting in an average speed of 6.2 m/s. The blades feature the NACA4413 airfoil along their entire length. The effects of manufacturing and assembly errors are included in the analysis by assuming normally distributed geometric uncertainty affecting the radial profiles of chord and twist. The objectives of the rotor RMDO are to maximize the mean of AEP and minimize its standard deviation. The blades' nominal geometry is defined by 13 geometric design variables, and 7 control variables correspond to the rotor speeds for the considered wind speeds $U_i = (5 + i)\ m/s,\ i = 1, 7$. A structural constraint on the maximum bending moment (BM) and an aeroacoustic constraint limiting the maximum rotor speed are enforced, and XFOIL is used to determine required airfoil data for WINSTRIP, an in-house BEM code. The single-objective RMDO problem is formulated as a 2-objective deterministic problem requiring maximization of mean AEP and minimization of its standard deviation. URQ is used to propagate uncertainty, and the 2-objective optimization is solved with a 2-stage multi-objective evolution-based optimization strategy: a multi-objective Parzen-based estimation of distribution (MOPED) algorithm yields an initial estimate of the optimum solution, or the Pareto front if multiple optima exist, and an inflationary differential evolution algorithm refines the MOPED estimate [11].

To highlight the improvements achievable by using RMDO, the robust design is compared to the solution of the corresponding deterministic design optimization, which ignores uncertainty. The deterministically optimum rotor has nominal AEP of $96,20\ kWh$, AEP expectation $\mu_{AEP} = 89,97\ kWh$. and AEP standard deviation $\sigma_{AEP} = 4,99\ kWh$. The probabilistically optimum rotor has nominal AEP of $95,00\ kWh$, $\mu_{AEP} = 91,62\ kWh$ and $\sigma_{AEP} = 2,78\ kWh$. Thus, σ_{AEP} of the robust design is more than 44 % lower than that of the deterministic design. For both rotors, the left subplot of Fig. 3 compares the nominal and mean estimates of the amount of AEP accounted for by each wind speed U. Both mean curves also report error bars of size $\pm\sigma_{AEP}$. The deterministic optimum has better nominal AEP curve, but worse mean AEP curve than the robust optimum. More importantly, the σ_{AEP} values of the deterministically optimal rotor are significantly higher than those of the probabilistically optimal rotor. The right subplot of Fig. 3 refers to the root bending moment of the two rotors, and highlights that the root BM standard deviation of the probabilistic optimum is lower than that of the deterministic optimum for all considered speeds.

As reported in [11], the power curves of the two optima do not differ significantly. This is because the robust optimum has lower rotational speeds but higher loading at nearly all radii and wind speeds, due to its lower blade twist and its lower rotational speed. The power loss due to lower rotational speeds compensates the power enhancement due to higher loading. Thus, the AoA α over most of the blade is higher for the probabilistic than for the deterministic design. More specifically, for the probabilistic design, AoA is in a region where the slope of the lift-AoA curve is shallower than for the deterministic design. Consequently, variations of AoA due to pitch errors results in smaller variations of the lift coefficient, the power and the generated energy of the ro-

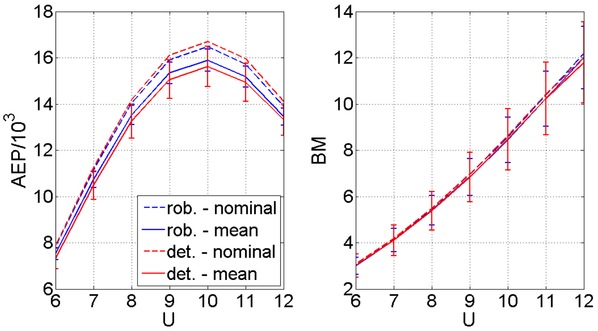

Figure 3. Performance of deterministic and robust small rotor designs. Left: proportion of AEP at each wind speed U $[m/s]$. Right: blade root bending moment $[kNm]$ against U.

bust design. This mechanism is highlighted by the mean and standard deviation of AoA and lift coefficient C_L of the two rotors reported in Fig. 4.

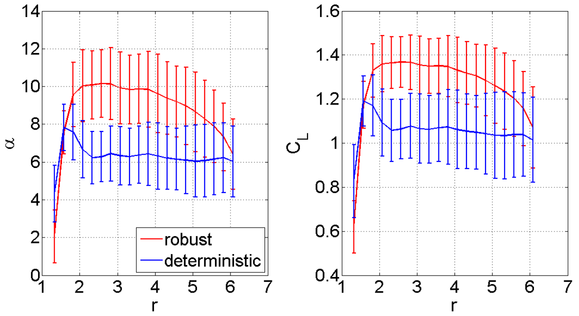

Figure 4. Performance of deterministic and robust small rotor designs at $U = 12$ m/s. Left: AoA α $[deg]$ against radius r $[m]$. Right: C_L against r.

4.2. COE optimization of 5 MW HAWT rotor

This study aimed at probabilistically minimizing the LCOE of the NREL 3-blade 5 MW 126 meter-diameter speed- and pitch-controlled turbine [6]. The uncertainty is due to the variability of the mean wind speed, arising either because the turbine is installed at sites with wind characteristics different from the design specification, or because of the long-term wind variability at a given site due to environmental factors such as climate change. The yearly frequency distribution of the wind velocity U at the hub height is taken to be a Weibull PDF with shape parameter of 2 and average speed varying between 7 and 13 m/s according to the uniform distribution. Composite Bezier curves are used to parametrize the airfoil geometry, and cubic splines are used to parametrize the radial distributions of blade pitch and chord. The considered 48 design variables are: 46 geometric parameters defining the blade outer shape, the tip speed ratio in the region between cut-in and rated wind speeds, and one scaling factor defining the relative thickness of all parts of the blade internal structure with respect to a reference structural design.

Structural constraints on ultimate loads, fatigue damage, buckling and maximum tip deflections are enforced. The aero-servo-elastic and stress analyses are performed using FAST, BMODES, and CO-BLADE, and the aerodynamic loads are determined with AERODYN using the force coefficients of XFOIL and AERODAS. The RMDO problem is solved by minimizing a weighted sum of mean and standard deviation of LCOE using the pattern search optimizer of MATLAB [13], a non-evolutionary deritative-free global search method. For each nominal design, mean and standard deviation of LCOE are computed using the analytical definitions of these two variables, and calculating the required integrals of LCOE over the given mean wind speed range.

The mean LCOE of the robust optimum is found to be about 6 % lower than that of the baseline turbine, and the LCOE standard deviation of the robust optimum is about 15 % lower than of the baseline. These improvements are achieved mostly through mass reduction and power curve enhancements of the robust optimum. The outer blade shape of the robust and baseline turbines differs significantly, as partly highlighted by the three subplots of Fig. 5, which compare the root, midspan and tip airfoils of the two turbines.

The left and right subplots of Fig. 6 report respectively the rotor speed and the electric power of the two turbines against the wind speed. One notes that the power extracted by the robust HAWT is higher than that of the reference turbine from cut-in to rated wind speed. It is also observed that the rotational speed of the robust turbine in this wind speed range is higher than for the reference turbine.

5. CONCLUSIONS

Numerous and significant sources of uncertainty in wind energy engineering demand the use of probabilistic design approaches, since a probabilistic definition of the producible wind energy is likely to better inform decision-making at scientific and governmental levels. This paper presented a brief description of the technologies used in HAWT rotor RMDO and the work performed by the author and his group in this area.

Important environmental uncertainty sources include the time- and space-variability of wind characteristics due to the vertical shear and the thermodynamic state of the atmospheric boundary layer (ABL) [32]. As an example, it was recently shown that omitting the effects of humidity fluxes in marine ABL thermodynamic state analyses can result in overpredicting by up to 4 % the mean wind speed at 150 meters, the hub height of several new large off-shore HAWTs [33]. The extent of these phenomena is expected to be strongly site-dependent, and such uncertainty ought to be accounted for in HAWT design.

Uncertain aerodynamic factors include the prediction of laminar-to-turbulent transition, near and

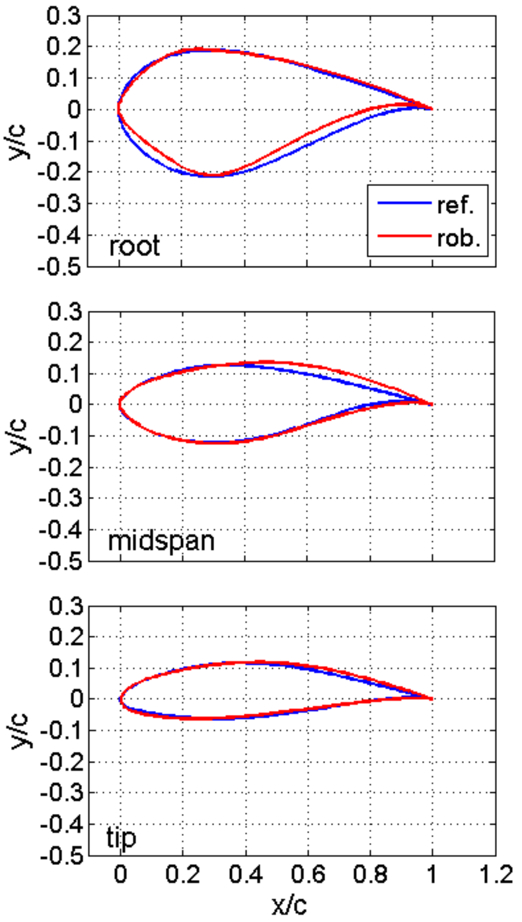

Figure 5. Comparison of airfoils of robust and conventional designs of 5 MW HAWT rotor.

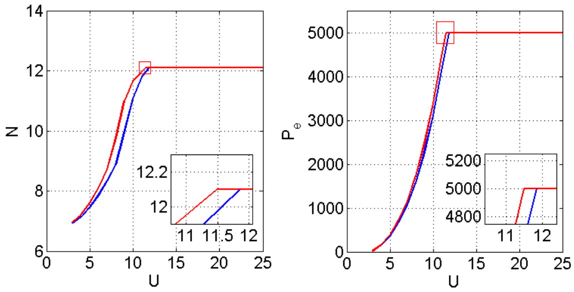

Figure 6. Regulation and power curve of robust and conventional designs of 5 MW HAWT rotor. Left: rotor speed N [*rpm*] against U. Right: electrical power P_e [kW] against U.

post-stall characteristics. Contributing factors to this uncertainty include the blade roughness levels varying during operation due to contamination, accretions and wear, and the turbulence intensity, but also the use of rapid but insufficiently accurate computational aerodynamics tools in HAWT design. Advances in this area, aimed at *a*) improving the prediction of the impact of transition and 3D flow effects on blade loads, and *b*) massively reducing the cost of the computational technologies needed to accomplish this are required.

Additional uncertainty to be considered in HAWT RMDO is that caused by input perturbations of the control system, such as inaccurate wind speed measurements, as well as insufficient accuracy of the HAWT models used to design the controller.

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