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CYCLIC CONTROL OPTIMIZATION FOR A SMART ROTOR

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ABSTRACT

The paper presents a method to determine cyclic control trajectories for a smart rotor undergoing periodic-deterministic load variations. The control trajectories result from a constrained optimization problem, where the cost function to minimize is given by the variation of the blade root flapwise bending moment within a rotor revolution. The method is applied to a rotor equipped with trailing edge flaps, and capable of individual blade pitching. Results show that the optimized cyclic control significantly alleviates the load variations from periodic disturbances; the combination of both cyclic flap and pitch allows to reduce the action (and hence the wear) on the pitch actuators, and still to achieve considerable load alleviation.

NOMENCLATURE

GF	generalized aerodynamic forces
J	optimization cost function
M_x	blade root flapwise bending moment
u	control action
β	flap deflection angle
ψ	blade azimuthal position

Abbreviations

Ref.	reference control
Col.P.	collective pitch
Col.F.	collective flap
CPC	cyclic pitch control
CFC	cyclic flap control
CPCF	cyclic pitch and flap control

INTRODUCTION

Several research works have recently focused on *smart-rotor* concepts [1]: wind turbine rotors that, through a combination of sensors, processing units, and actuators, are able to actively alleviate the variation of the loads they are subject to, thus reducing the load requirements the structure has to withstand. Most of the load variations experienced by the wind turbine rotor originate from fluctuations in the flow field encountered by the rotating blades; the variations have a stochastic nature, mainly related to wind turbulence, but also an important deterministic periodic component [2], which originates, for instance, from terrain shear effects, tower passage, rotor misalignment. The periodic load variation, as such, is easily predictable, and its knowledge can enhance the load alleviation performances of the smart rotor. In their smart rotor controller, Van Wingerden et al. [3] include predictions on periodic load variations in the form of a feed-forward term; Houtzager et al. [4], starting from a lifted system representation, propose a repetitive control where cyclic pitch variation address exclusively periodic load variations.

The present work proposes a simple cyclic control formulation, where the control signal only depends on the blade azimuthal position, and follows a periodic trajectory, repeated at each rotor revolution. The control trajectory results from a constrained optimization problem, where the cost function is given by the variations of the flap root flapwise bending moment. The optimization is simply based on measurements of the bending moment, and does not require any further knowledge on the controlled system.

The literature reports widespread figures on the load alleviation performances of smart rotors, see for instance the summary compiled in Barlas et al. [5]. Load alleviation depends, in fact, on a multitude of factors (simulation conditions, sensors choices, actuator setup, and control algorithm, among others), and is often difficult to distinguish the impact on load alleviation from each single factor. The control setup proposed in the study does not depend on additional sensors measurements, nor on a particular control algorithm, therefore, due to its simplicity, it could provide a standard ground to evaluate the performances of different smart rotor concepts, and would facilitate the comparison between actuator types and setups. The results from the cyclic optimization will also provide a useful term of comparison for future implementations of more complex feedback control algorithms.

The smart rotor configurations investigated in this study include collective flap deflection (*Col.Fl.*), cyclic pitch (*CPC*), cyclic flap (*CFC*), and a combination of both cyclic pitch and cyclic flap acting together (*CPCF*). To better evaluate the different control strategies, an attempt is made to estimate the energy requirements for each of the investigated control strategies.

The proposed method has some important limitations, which are inherent in the chosen optimization procedure. The method can not be used to assess the performances of smart rotors in alleviating the effects of stochastic load variations, caused, for instance by wind turbulence, as the proposed control algorithm can only address periodic disturbances. Furthermore, the method can not be directly applied to more realistic conditions. In fact, as the optimization procedure receives no other information on the state of the plant, any variation in the cost function is reckoned as a consequence of a variation in the control optimization variables. Therefore, the optimization procedure can be carried out only with no other disturbances affecting the state of the plant, so that atmospheric turbulence, and time variations of the wind speeds have to be excluded from the simulation. More complex cyclic control methods could eventually overcome such limitations, for instance using iterative learning or repetitive control algorithms, as in Houtzager et al. [4].

In spite of its limitations, the proposed method allows for simple preliminary studies of smart rotor set-ups, and allows to compare different actuators configurations on the same basis, and set a term of reference for future controller development.

METHOD

The cyclic control trajectories are determined by solving a constrained optimization problem where the cost variable is evaluated from aeroelastic simulations of the NREL 5 MW reference turbine [6]. The turbine standard controller is applied, and the pitch control signals returned by the optimization are simply super-imposed to the reference signal from the standard controller. The turbine blades are equipped with trailing edge flaps, which cover 20% of the blade span, from 77.6% to 97.6% of the blade radius. The flaps extend for 10% of the chord length, and their deflection is limited to ± 10 degrees, returning variations of the steady lift coefficient from -0.45 to $+0.41$. The wind field in the simulations is purely deterministic; it accounts for tower shadow effects, and for the terrain shear as prescribed in the IEC standard [7].

The response of the turbine is simulated with the aeroelastic code HAWC2 [8], which couples multi-body structural dynamics with a BEM-based aerodynamic formulation; in order to capture the aerodynamic effects of the flap deflection, the unsteady aerodynamic model *ATEFlap* [9] is adopted. To reduce the simulation time, in this study aeroelastic simulations are run with a simplified model, where the structural degrees of freedom have been excluded, thus describing an ideally stiff turbine. The results are then compared, for selected wind speeds, against the ones returned by the full model, which includes all the structural degrees of freedom and multi-body dynamics; similarity and differences from the stiff turbine results are commented in the text.

The solution to the constrained optimization problem returns the cyclic control trajectory $u(\psi)$, which prescribes, as function of the blade azimuthal position ψ, the control actions to be repeated at each rotor revolution, and on each of the three blades. The optimization cost function J is evaluated within a complete rotor revolution, yielding to the constrained optimization problem:

$$\min_{u(\psi)} J_{\psi:[-\pi,+\pi]}, \tag{1}$$

subject to the control signal constraints:

$$u(\psi) \in \mathbb{R} | -10^\circ \leq u \leq +10^\circ, \text{ for the flap actuators, and}$$
$$u(\psi) \in \mathbb{R} | -90^\circ \leq u \leq +90^\circ, \text{ for the blade pitch.}$$

The problem is solved iteratively using the gradient-based constrained optimization algorithm described in Waltz et al. [10].

The cyclic control trajectory $u(\psi)$ is a continuous signal, which would render the optimization problem infinite-dimensional. To limit the problem dimension, the continuous trajectory $u(\psi)$ is described by a finite set of values x_i, which prescribe the control value at fixed azimuthal locations ψ_i; the control signal among the fixed points is determined using Piecewise Cubic Hermite Interpolating Polynomials (PCHIP) [11]. The optimization variables are given by the values of the the fixed points x_i, plus an additional variable returning the phase shift of the predetermined azimuthal locations of the points. In this work, six points are used to describe the cyclic control trajectories, giving thus six plus one optimization variables.

The cost function minimizes the amplitude of the variations on the blade root flapwise bending moment M_x; in addition, to avoid the trivial solution of down rating the turbine operation to reduce the loads, a strong penalization is added for power output

P_{avg} descending below rated power P_0:

$$J_{ar} = (\max M_x(\psi) - \min M_x(\psi))^2 + \rho_{\mathrm{pow}} \left(\max\left[P_0 - P_{\mathrm{avg}}, 0\right]\right)^2. \quad (2)$$

The case of both cyclic pitch and cyclic flap acting together (*CPCF*) also includes a small penalty on the amplitude of the pitch angle variation, so to favor the less energy consuming flap action.

The operating wind speed considered in the optimization are 12, 16, 20, 24 m/s, and the following control strategies are considered:

- Reference (*Ref.*), the NREL standard controller keeps the rotor near rated rotational speed, and power limitation is achieved by collective pitching to feather.
- Collective flap (*Col.F.*), all the flaps sections are deflected to negative values, so to decrease the load on the outer part of the blades, while decreasing the collective pitch value allow to maintain the same power output. The solution is conceptually similar to a collective partial pitch on the outer span of the blades.
- Cyclic pitch (*CPC*), the blade pitch follows the cyclic control trajectory returned by the optimization; the pitch angle of each blade is a function of the azimuthal position, while the mean pitch level is regulated by the standard controller.
- Cyclic flap (*CFC*), the flap deflection follows the optimized control trajectory; the collective blade pitch angle is determined by the standard controller.
- Cyclic pitch and flap (*CPCF*), the optimization returns a control trajectory for the blade pitch angles, and another for the flap deflection values.

ESTIMATION OF ACTUATION ENERGY

An attempt is made to quantify the energy required to modify the blades pitch angle, and the deflection of the flap sections. The problem is rather complex, and highly dependent on the actuator devices used to perform the control action. Only a very simplified estimation is given here, assuming steady conditions, linearity, and neglecting the energy requirements of the physical actuator devices; the results are thus to be intended more as general guidelines, and indications of the actuator wear, rather than as rigorous figures.

The energy required to modify the blade pitch angle of one degree $E_{d\theta}$ is evaluated simply as the mean pitch moment at the blade root M_z over a complete rotor revolution:

$$E_{d\theta} = \frac{1}{2\pi}\int_{-\pi}^{\pi} M_z(\psi)\frac{\pi}{180}\mathrm{d}\psi \qquad [J/deg] \quad (3)$$

The estimation of the energy requirement for one degree flap deflection $E_{d\beta}$ is derived from the expression of the aerodynamic general forces on an airfoil with flap, as expressed in [12], and [13]. The generalized force on the airfoil is computed as the sum of four contributions, depending on: angle of attack at three-quarter chord $GF_{\alpha 3/4}$, airfoil camber-line GF_{cmb}, flap deflection GF_{β}, and flap deflection rate $GF_{\dot\beta}$:

$$\begin{aligned}
GF &= GF_{\alpha 3/4} + GF_{\mathrm{cmb}} + GF_{\beta} + GF_{\dot\beta},\\
GF_{\alpha 3/4} &= -2\rho b_{hc} U_0^2 \mathrm{PI}_5^{\beta} \cdot \alpha_{3/4},\\
GF_{\mathrm{cmb}} &= \rho b_{hc} \frac{U_0^2}{\pi}\left(\mathrm{PI}_8^{\beta,\mathrm{cmb}} + \mathrm{PI}_5^{\beta} H_{\mathrm{dydx}}^{\mathrm{cmb}} - H_{\mathrm{dydx}}^{\mathrm{cmb}}\mathrm{PI}_7^{\beta}\right),\\
GF_{\dot\beta} &= \rho b_{hc} \frac{U_0}{\pi}\left(\mathrm{PI}_5^{\beta} H_y^{\beta} + b_{hc}\mathrm{PI}_3^{\beta} - H_y^{\beta}\mathrm{PI}_7^{\beta} + \mathrm{PI}_9^{\beta}\right)\cdot\dot\beta,\\
GF_{\beta} &= \rho b_{hc} \frac{U_0^2}{\pi}\left(\mathrm{PI}_8^{\beta,\beta} + \mathrm{PI}_5^{\beta} H_{\mathrm{dydx}}^{\beta} - \mathrm{PI}_7^{\beta} H_{\mathrm{dydx}}^{\beta}\right)\cdot\beta, \quad (4)
\end{aligned}$$

where, b_{hc} is the chord half length, and U_0 is the relative flow speed on the airfoil. $PI_{\#}^{x}$, and $H_{\#}^{x}$ are deflection shape integrals, as specified in Gaunaa [12]; the suffix β refers to shape integrals of the flap circular arc deflection shape, while *cmb* refers to integrals of the camber-line shape (a NACA 6417 camber is assumed).

The energy required to deflect the flap from zero to $\Delta\beta$ on a unit span airfoil section $E_{d\beta}^{dZ}$ is then evaluated as the integral of the generalized forces times the flap deflection. Assuming the terms on the angle of attack, and camber are constant in β, and that the flap deflection rate $\dot\beta$ is also constant, the integral simplifies to:

$$\begin{aligned}
E_{d\beta}^{dZ} &= \frac{1}{\Delta\beta}\int_0^{\Delta\beta} GF\,\mathrm{d}\beta\\
&= GF_{\alpha 3/4} + GF_{\mathrm{cmb}} + GF_{\dot\beta} + \frac{1}{\Delta\beta}\int_0^{\Delta\beta} GF_{\beta}\,\mathrm{d}\beta. \quad (5)
\end{aligned}$$

The term depending on the flap deflection rate is scarcely significant when compared to the other terms, and is therefore omitted. The energy estimation is then depending on the considered flap range $\Delta\beta$, which is here chosen to 10 degrees, corresponding to half the total flap range. The total energy required to deflect all the flaps on a blade is then computed as the summation of the energy at each airfoil section times its spanwise extension.

The energy requirements for flap deflection and pitch variation are estimated at different operating mean wind speed, assuming steady conditions. The requirements are referred to a single degree actuation (fig. 1), and assume that the same energy is required for actions in both directions. Although largely approximative, the estimations indicate that the energy required to pitch the whole blade of one degree is from 20 to 90 times larger than the energy required to deflect the flaps covering the outer 20 % span of the same blade.

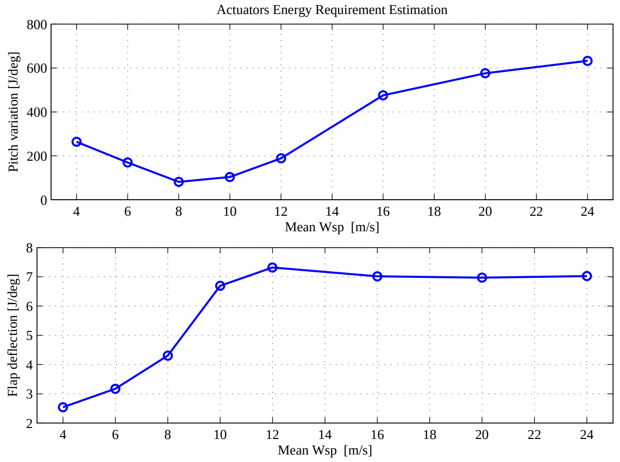

FIGURE 1. Indicative estimation of the energy requirements for actuators actions, comparison between pitch variation (top) and flap deflection (bottom); values referred to one degree actuation for a single blade with flaps covering 20% span.

OPTIMIZED CONTROL FOR LOAD ALLEVIATION

First, a very simple control strategy is investigated by deflecting completely the flaps upwards. The aerodynamic loads on the outer part of the blade are reduced, while rated power is maintained by decreasing the blades pitch angle. The setup is similar to a partial blade pitch, and the mean blade root bending moment is lowered, but its azimuthal variation, and the fatigue loads, are nearly the same as in the reference case (fig. 2).

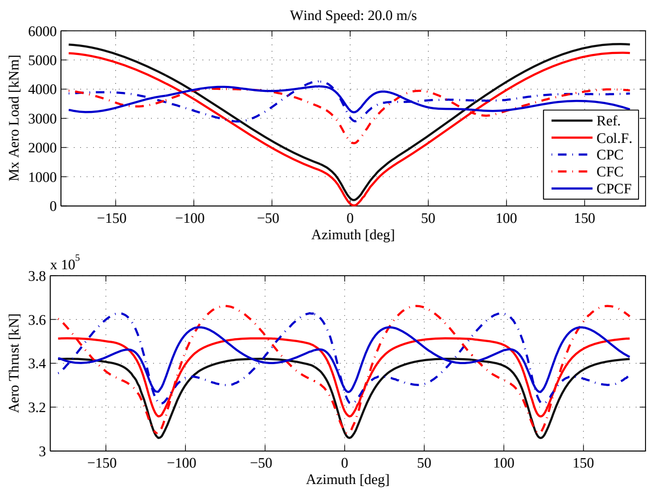

FIGURE 2. Load alleviation, example at 20 m/s of load variation on the blade root flapwise bending moment (top), and thrust on rotor (bottom) with the reference controller and the optimized control trajectories.

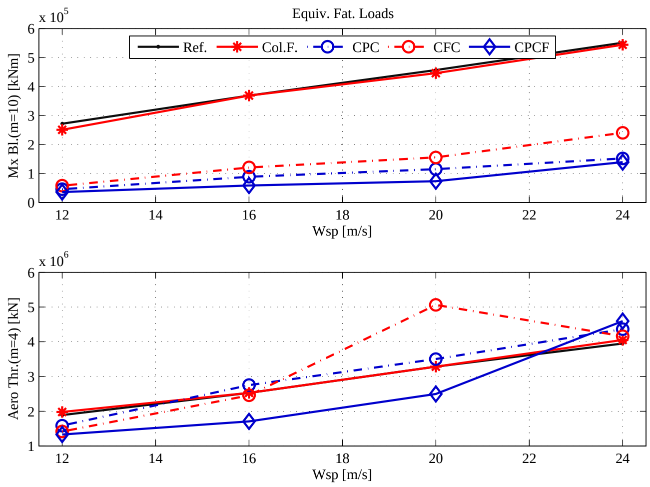

FIGURE 3. Load alleviation, equivalent fatigue loads for the reference controller, and the optimized control trajectories. The equivalent loads correspond to a full rotor revolution referred to 600 cycles, and are based on the blade root flapwise bending moment (top), and on the rotor thrust force (bottom).

The optimized cyclic trajectories for the pitch (CPC) and flap (CFC) control returns slightly higher mean loading on the blade, but a significant reduction of the blade root load variation (fig. 2, top). The corresponding equivalent fatigue loads (fig. 3, top) are nearly one-quarter of the fatigue loads reported in the reference case; Houtzager et al. [4] report similar reductions with an individual pitch repetitive controller.

The optimized control trajectories (fig. 4) try to compensate for the variations in the wind field encountered by the rotating blade: when the blade is pointing downwards (0° azimuth) the aerodynamic forces are increased by reducing the pitch angle, or increasing the flap deflection, so to compensate for the decrease in wind speed. The trajectories reach their maximum (or minimum) *before* the blade passes in front of the tower; the optimization procedure is thus able to correctly identify, and anticipate, the delay in the response of the system.

Cyclic pitch control achieves higher load alleviation than cyclic flap, especially at wind speed of 20 and 24 m/s, where the flap has reached the limits of the deflection range (fig. 4). The required flap deflection is much higher (approximately five times) than the variation in pitch angle; on the other hand, the energy required by the cyclic pitch control is from 10 to 20 times higher than required by the cyclic flap (fig. 5).

By combining cyclic pitch and cyclic flap control, and adding a small penalty to the pitch action, the advantages of the two strategies are combined (CPCF series in fig.4– 5). The cyclic flap control compensate for most of the load variation at lower wind speeds, while the cyclic pitch contribution takes over once the flap has reached the deflection limits. The energy consump-

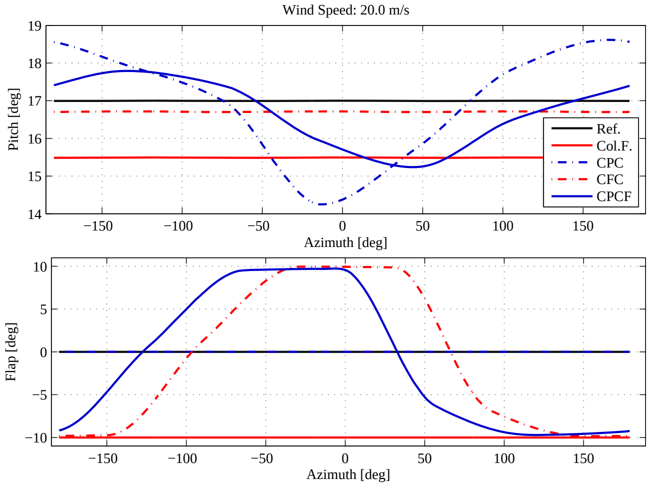

FIGURE 4. Load alleviation, example at 20 m/s of the cyclic control trajectories optimized for blade root load alleviation. Pitch (top) and flap (bottom) control signals.

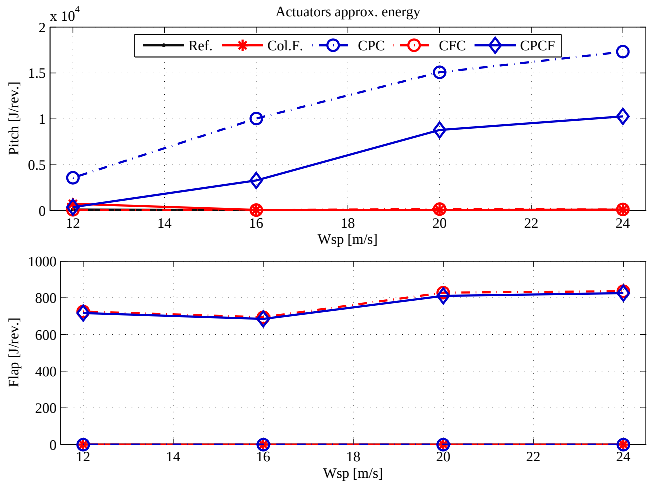

FIGURE 5. Load alleviation, estimation of the energy requirements for the flap and the pitch control actions performed at each rotor revolution following the optimized control trajectories.

tion, and hence the actuators wear, is lowered to nearly half the case of the cyclic pitch control alone, and the equivalent fatigue loads are reduced to 15% of the reference ones.

The variation in the thrust force (fig. 2), and the corresponding equivalent fatigue loads (fig. 3), which were not part of the optimization, are increased by the cyclic control actions. Simulations including all the structural degrees of freedom return similar figures in terms of blade root load alleviation, although the displacement required to both pitch and flap actuators is higher, as the flexibility of the blade reduces the effects of the control actions. Simulations with the flexible turbine model also show a significant increase in the variation of the tower bottom fore-aft bending moment, especially for the cases involving flap cyclic action. If confirmed, future work should consider including a penalty for the tower load variation in the optimization cost function.

CONCLUSION

The optimized control trajectories show that cyclic control can significantly reduce the fatigue loads on the blade root flapwise bending moment caused by deterministic variations of the aerodynamic loads. Reductions of nearly 75% are reported for cyclic pitch control, wheras cyclic flap control returns a lower reduction, approximately 70%, since, especially at high wind speeds, the flap reaches its deflection limits. Particularly good results are obtained by combining the cyclic pitch and flap actions; the equivalent fatigue loads from deterministic variations of the aerodynamic forces are reduced to 15% of the loads in the reference case, and the presence of the flaps lowers to nearly half the requirements on the pitch actuators action.

Few simulations with a fully flexible model have confirmed the load alleviation potentiality, but have also highlighted an important increase in the tower bottom fatigue load, which should be addressed in future investigations.

To conclude, within its limitation, the proposed optimization method proved adequate to quantify in a simple manner the potentiality of different smart-rotor control configurations to compensate for periodic variations in the wind field. The method can be also applied to other objectives, as, for instance, to evaluate the potential of increasing the energy output below rated conditions by exploiting smart rotors control possibilities.

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