Model-free based pitch control of a wind turbine blade section in the OpenFAST environment - Some technical remarks

Loïc Michel*

October 4, 2024

Abstract

In the OpenFAST environment, the local aerodynamic lift of a wind turbine blade is controlled taking into account several operating conditions. This brief deals with a preliminary study of a model-free based control algorithm that tracks the lift considering the internal aerodynamic modeling provided by OpenFAST. Some numerical results are presented considering some operating conditions under stochastic wind inflow as well as the introduction of a basic maximum lift tracking algorithm, dedicated to maximize the lift at the blade scale.

1 Introduction

To optimize the energy extraction from the wind, the control is performed from the generator side to optimize rotor loads i.e. power extraction versus blade fatigue. The control of the local aerodynamic flow around the blade may constitute an alternative to cope with turbulences minimization and reduce the fatigue of the blade.

Blade pitch control research is currently very active within wind turbine trends [Njiri and Söffker(2016)] since it addresses methodologies to cope with structural load reduction for which advanced control methods have been proposed. Recently, an alternative model-free controller [Michel(2018)], whose structure is close of [Fliess and Join(2013)], has been numerically experimented within the high fidelity environment ISIS-CFD [Queutey and Visonneau(2007)] in order to track the lift to a desired reference through the pitch angle of the blade [Michel et al.(2024)]. To extend this study to the global wind turbine scale i.e. to investigate the properties of controlling locally the aerodynamic at the blade scale by taking into account the dynamic of the wind turbine structure, this work proposes a preliminary study in the OpenFAST environment of the

*Loïc Michel is with Nantes Universite-École Centrale de Nantes-LS2N, UMR 6004 CNRS, Nantes, France.

lift tracking at the blade scale in several stochastic wind inflow conditions. The goal is to illustrate some robustness properties of the proposed model-free based control algorithm, considering the mechanical structure as well as the dynamic of the lift with respect to the rotation of the blades.

OpenFAST is a framework developed by NREL [OpenFAST(2024)] for simulating the coupled dynamic response of wind turbines. The Matlab toolbox "Lift Control OpenFAST & Stabilization" (LCO/St) helps to use OpenFAST as a complete 'toolchain' to simulate the dynamic behavior of wind turbines towards the development of advanced control laws algorithms [Michel(2024)].

Following the first pre-release of LCO/St (v1.8.0 - Aug. 21, 2024 and its associated user guide), this report provides some additional results that illustrate stochastic conditions of the wind inflow as well as a very basic maximum lift tracking algorithm. These results are available within the LCO/St release (v1.8.2 - Oct. 4, 2024 and its associated user guide).

The report is organized as follow. Section 2 presents the methodology including the definition of the model-free based control algorithm and the coupling scheme with the OpenFAST simulator. Section 3 provides simulation results spanning some operating conditions including first experiments with the proposed maximum lift tracking strategy. Section 4 concludes the paper. Some Matlab and OpenFAST instructions are given to help the user to process the simulation cases.

2 Model-free based control law methodology

2.1 Presentation

A model-free control, designated as "para-model control", without derivative term but with an integrator associated to a forgetting factor was proposed in [Michel(2018)]:

$$u_k = \Psi_k \, . \int_0^t K_i (y_k^* - y_k) \, d\,\tau \tag{1}$$

where k is the discrete iteration index and Ψ_k is a time series that "adjusts" online the gain of the integrator. The term Ψ is given by:

$$\Psi_k = \Psi_{k-1} + K_p (K_\alpha e^{-K_\beta . k} - y_k) \tag{2}$$

In (1)-(2), u_k is the control output ; y_k^* is the output reference trajectory; y_k is the output of the controlled system; K_p, K_I, K_α and K_β are real positive tuning gains.

Remark that in (1), in order to minimize the influence of measurement noise, no output numerical derivative is used, and only an integral term appears, which is very favorable in terms of minimizing the influence of measurement noise. In fact, integration of the noisy output y_k is only sensible to the noise average. For example, this approach is in line with that of ALIEN differentiator [Fliess and Sira-Ramírez(2008)], where integration terms are used to avoid problem on differentiation of noisy signal. Moreover, roughly speaking, in equation (2), there is a memory effect with the term Ψ_{k-1} and a forgetting target factor generated by the exponential function $K_\alpha e^{-K_\beta . k}$.

2.2 Coupling between control and OpenFAST

The lift tracking is achieved through a control loop wherein the control input of the system (actuator + blade) is a DC motor. Figure 1 presents the scheme of the proposed discrete closed-loop where the control is sampled at $T_s = 0.045$: u_k is the control input (assimilated to the voltage applied to the DC motor), α_k is the pitch angle and F_k is the lift force calculated by OpenFAST. The DC motor, that drives the blade pitch angle, is modeled as a first order transfer function of time constant $\tau = 10$ s. A first-order filter has been added to the simulated lift to damp the oscillations of lift that result from the blade rotation. Depending on the wind turbine operation, the reference F_k^* can be either pre-defined by the user or self-adjusted thanks to the maximum lift tracking algorithm, which requires the simulated lift as well as the pitch angle to deduce how to "move" the lift reference.

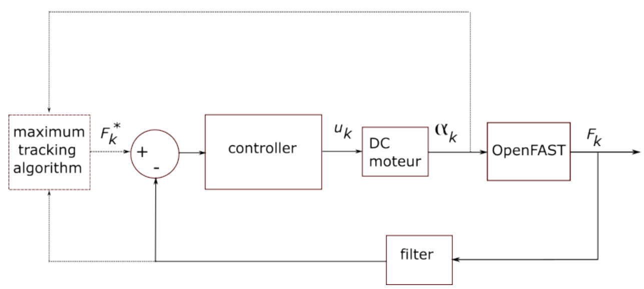

Figure 1: Schematic of the control loop for lift tracking.

3 Numerical results

The NREL 5 MW wind turbine is considered within the controlled node #9, and the prefixed-'TPO' input files are considered to compute the following cases[1] (see the user guide of LCO/St). The output torque and power of the generator have been modeled using a basic relationship under Simulink[2].

3.1 Open-Loop computation

The open-loop computation[3] allows rating the generator (close to 5 MW) under a constant wind inflow speed of 13 m/s and a pitch angle of zero degree[4]. It is also possible to compute the C_L curves (see the user guide of LCO/St). Figure 2 displays the generator output power and torque associated to the rotation speed.

Figure 2: Open-loop behavior of the generator and rotor speed.

---

[1]The recommended settings are: (AeroDyn15) `WakeMod = 2`, `AFAeroMod = 2`, `AIDrag = True`, `TIDrag = True`, `IndToler = 1e-10`, `MaxIter = 1000` (ElastoDyn) `GenDOF = True` `TwFADOF1 = True`, `TwFADOF2 = True`, `TwSSDOF1 = True`, `TwSSDOF2 = True`, `RotSpeed = 11`, `PtfmSurge = 0`, `PtfmPitch = 0`. Also in (Servodyn), `VSContrl = 4` to allow the generator to be controlled by Simulink.

[2]The control of the generator by Simulink must be activated by seeting `VSContrl = 4`.

[3]The following Simulink file is used `OpenLoop_Kernel_1B.slx`.

[4]A 'tower strike' occurs during the simulation if a stochastic wind (13 m/s) is used.

3.2 Lift tracking under constant inflow speed

The closed-loop computation[5] illustrates the control of the lift that tracks a constant reference set to 1500 N considering a constant wind inflow speed of 13 m/s. Figure 3 illustrates the controlled lift (that tracks the reference of 1500 N) according to the pitch that stabilizes, in this case, around 6 degrees.

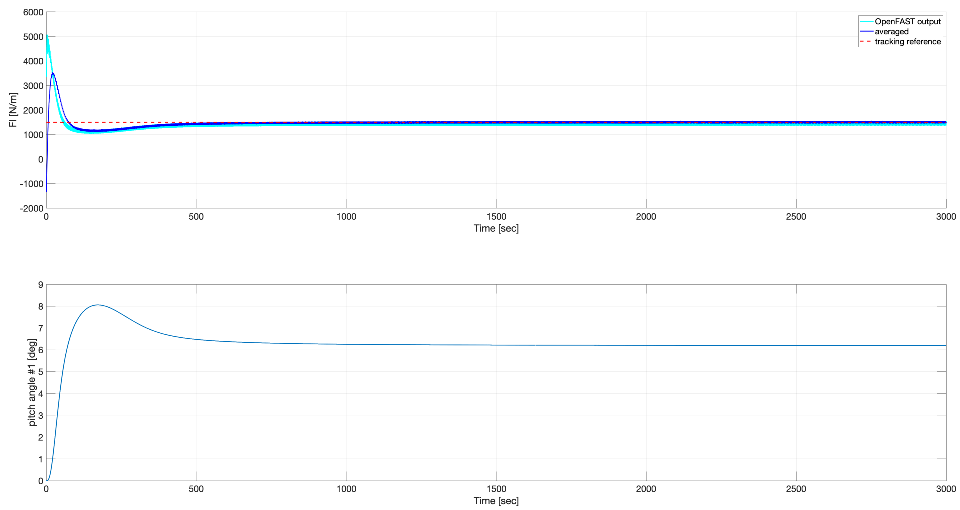

Figure 3: Closed-loop stabilization of the lift (ref. = 1500 N) under a constant wind inflow speed of 13 m/s.

[5]The following Simulink file is used: `ClosedLoop_Kernel_LiftCntrl_1A_2.slx`.

3.3 Stochastic inflow speed

The closed-loop computation[6] illustrates in this section the control of the lift that tracks a constant reference set to 1500 N considering a stochastic wind inflow speed averaged at 13 m/s[7] [8] [9]. Figure 4 illustrates the controlled lift (that tracks the reference of 1500 N) according to the pitch that 'follows' the variations of the wind speed profile.

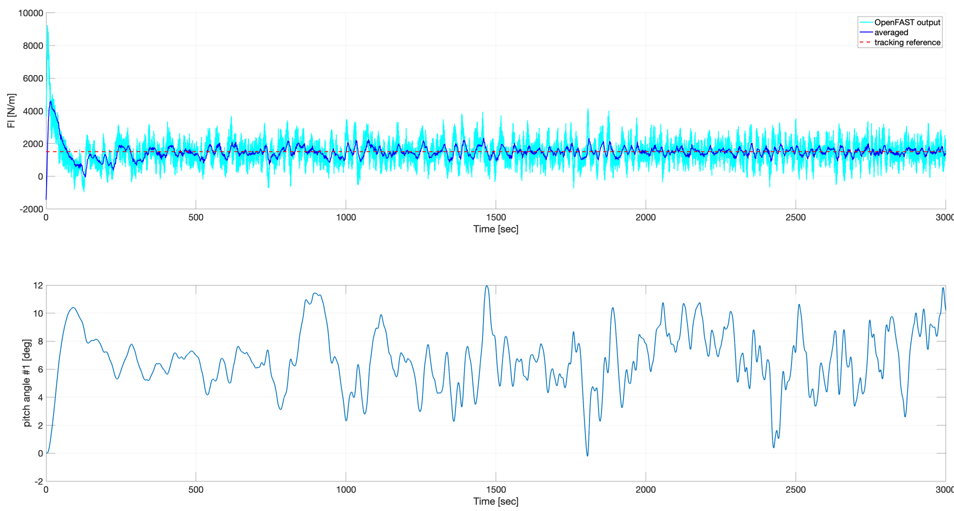

Figure 4: Closed-loop stabilization of the lift (ref. = 1500 N) under a stochastic wind inflow speed of 13 m/s.

[6]The same Simulink file is used: `ClosedLoop_Kernel_LiftCntrl_1A_2.slx`.

[7]The software TurbSim v2.0 (Windows version) has been used to generate, from the .inp input file, the stochastic time-series of the wind profile. The generated '.bts' and '.wnd' files are processed by OpenFAST through the input file 'InflowWind'.

[8]TurbSim can be downloaded at `https://www.nrel.gov/wind/nwtc/turbsim.html` (used v2.00.07a-bjj).

[9]**Warning:** the TurbSim files (.bts) provided in the GitHub repository are under-sampled wind profiles (computed at very low resolution), which are not suitable for the simulation cases. It allows checking the simulation 'toolchain' but it does not reproduce the results of this report. The time-series (regarding the 13 m/s and 18 m/s) shall be re-generated from the original .inp files provided in the 'TurbSim_v2_files' directory.

3.4 Basic lift self-maximization

The goal is to track the maximum of the lift using kind of gradient step descent[10] and is described as follow.

Denote F_k, the current value of the simulated lift at the instant k and F_{k-1} the value of the lift at the precedent instant $k-1$. Denote also α_k the current value of the pitch angle at the instant k.

$F_{gradient}(k=0) \leftarrow 1$
if $F_k > F_{k-1}$ **then**
  $F_{gradient} \leftarrow \beta * F_{gradient}$
end if
if $F_{k-1} > F_k$ **then**
  $F_{gradient} \leftarrow -F_{gradient}$
end if
if $\alpha < \alpha_c$ **then**
  $F_{gradient} \leftarrow -\gamma$
end if
$F_{update} \leftarrow F_{update} + \delta * F_{gradient}$

The principle is to "update" (increase or decrease) the reference F_{update} thanks to the equation $F_{update} = F_{update} + \delta F_{gradient}$ with respect to the sign of the difference $F_k - F_{k-1}$ that is proportional to the gradient $F_{gradient}$ (the parameter δ is the time-step of the F_{update} dynamic). The dynamic of the reference update is more favorable to increase the lift reference, hence fixing $\beta > 1$ than decreasing it, despite the variations of the blade pitch. To prevent from unexpected aerodynamic behavior if the wind inflow speed becomes very low, the lift reference is forced to strongly decrease with a γ-rate if the blade pitch remains below a critical angle α_c, while tracking a higher lift.

Numerical experiments[11] have been performed with $\beta = 1.2$, $\gamma = 1.5$, $alpha_c = 0$ and considering a stochastic inflow wind speed of 13 m/s (Fig. 5) and a stochastic inflow wind speed of 18 m/s (Fig. 6)[12] .

[10] `https://en.wikipedia.org/wiki/Maximum_power_point_tracking`

[11] The following Simulink file is used: `ClosedLoop_Kernel_LiftCntrl_1B.slx`.

[12] The case 18 m/s produces a 'tower strike' during the simulation! A solution that overcomes this fault is to set `GenDOF = False` in the ElastoDyn file (the modification is made automatically in the corresponding config file) but this solution is not at all satisfactory!

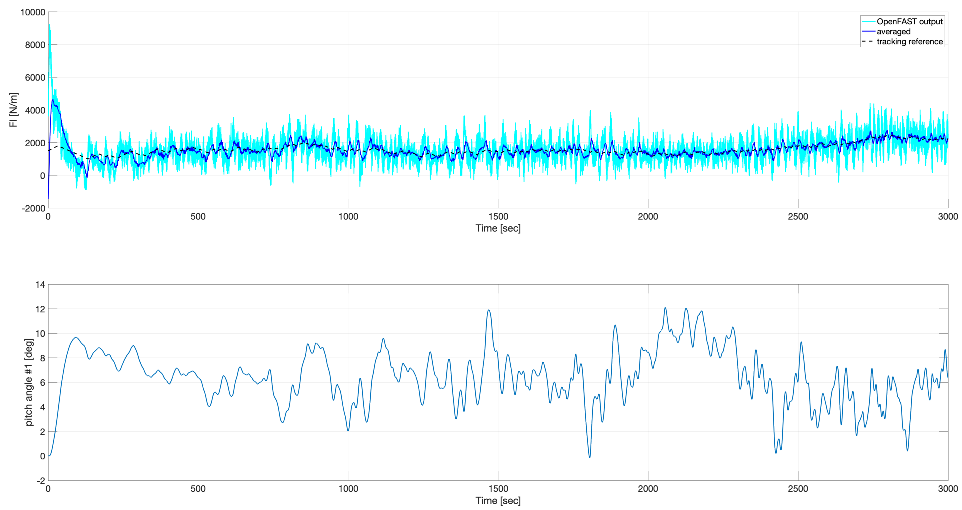

Figure 5: Max. lift tracking under a stochastic wind inflow speed of 13 m/s.

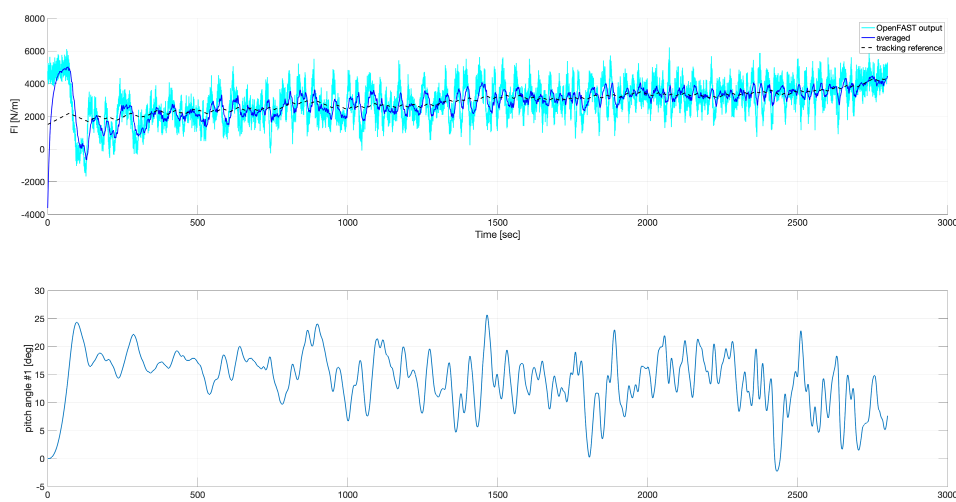

Figure 6: Max. lift tracking under a stochastic wind inflow speed of 18 m/s.

Acknowlegment

The author is grateful to Dr. Jean-Christophe Gilloteaux, Dr. Thomas Potentier (INNOSEA company) and M. Maximilien André (ECN/LHEEA lab) for their assistance and support regarding the utilization of OpenFAST. The author is also grateful to Dr. Pierre Molinaro for his assistance regarding the compilation and installation of OpenFAST. The author is also sincerely thankful to Prof. Jean-Pierre Barbot (ECN/LS2N & ENSEA/QUARTZ) for his constant guidance and support.

This work has been supported by the GOWIBA project that is funded by the Carnot Institute Marine Engineering Research for "Sustainable, Safe and Smart Seas".

References

[Fliess and Join(2013)] Michel Fliess and Cédric Join. 2013. Model-free control. *International Journal of Control* 86, 12 (Dec. 2013), 2228–2252.

[Fliess and Sira-Ramírez(2008)] Michel Fliess and Hebertt Sira-Ramírez. 2008. *Closed-loop Parametric Identification for Continuous-time Linear Systems via New Algebraic Techniques.* Springer London, London, 363–391.

[Michel(2018)] Loïc Michel. 2018. A para-model agent for dynamical systems. *preprint arXiv* (2018). arXiv:1202.4707 `https://doi.org/10.48550/arXiv.1202.4707`

[Michel(2024)] Loïc Michel. 2024. Lift Control OpenFAST and Stabilization - A model-free based control perspective. `https://hal.science/hal-04674957`

[Michel et al.(2024)] Loïc Michel, Emmanuel Guilmineau, Caroline Braud, Franck Plestan, and Jean-Pierre Barbot. 2024. Model-Free Based Pitch Control of a Wind Turbine Blade Section: Aerodynamic Simulation. In *2024 European Control Conference (ECC)*. 657–662. `https://doi.org/10.23919/ECC64448.2024.10590742`

[Njiri and Söffker(2016)] Jackson G. Njiri and Dirk Söffker. 2016. State-of-the-art in wind turbine control: Trends and challenges. *Renewable and Sustainable Energy Reviews* 60 (2016), 377–393.

[OpenFAST(2024)] OpenFAST. 2024. OpenFAST website. `https://openfast.readthedocs.io/en/main/`

[Queutey and Visonneau(2007)] Patrick Queutey and Michel Visonneau. 2007. An interface capturing method for free-surface hydrodynamic flows. *Computers & Fluids* 36, 9 (2007), 1481–1510. `https://doi.org/10.1016/j.compfluid.2006.11.007`