Nacelle LiDAR online wind field reconstruction applied to feedforward pitch control

To cite this article: F. GUILLEMIN et al 2016 J. Phys.: Conf. Ser. 753 052019

View the article online for updates and enhancements.
Nacelle LiDAR online wind field reconstruction applied to feedforward pitch control

F.GUILLEMIN, D.DI DOMENICO, N.NGUYEN, G.SABIRON
IFPEN, 1 avenue de Bois-Préau, 92500 Rueil-Malmaison, France

M.BOQUET
LEOSPHERE, 16 rue Jean Rostand, 91400 Orsay, France

N.GIRARD, O.COUPIAC
MAIA EOLIS, Tour de Lille, Boulevard de Turin, 59777 LILLE , France

fabrice.guillemin@ifpen.fr

Abstract: This paper presents innovative filtering and reconstruction techniques of nacelle LiDAR data, and exploitation of obtained wind anticipation capabilities for wind turbine control strategy. The implemented algorithms are applied under industrial constraints, on a MAIA EOLIS wind turbine, equipped with a LEOSPHERE 5-beams pulsed LiDAR, during experimental campaigns of SMARTEOLE collaborative project.

1. Introduction and work objectives

Control strategies for wind turbine load mitigation have been widely studied in literature since the last decades [1]. Most of advanced control strategies have been developed and tested either on simulations or during field tests. More details regarding advanced control design for wind turbine can be found in the well detailed introduction of [2]. LiDAR sensors are a promising technology for the measurement of incoming wind. The ability to measure the upcoming wind in front of a wind turbine leads to great improvements in wind turbines control solutions. As shown in [1,3-4] this leads to load mitigation improvement mainly through blade pitch control and potentially to some production improvement through yaw control. Using LiDAR measurements allows estimating and anticipating the wind profile across the rotor and gives valuable information on the aerodynamic impacting the wind turbine. Therefore, classical feedback control strategies can be upgraded with new approaches, relying on the information provided by the LiDAR as in [5-7] with model predictive control, and [8-10] with feedforward control, which are just a few. Rotor effective wind speed anticipation is the key element to highly decrease the mechanical solicitation on the structure, the tower, the transmission and the blades, allowing cost reduction on the wind turbine itself and a reduced levelized cost of energy. Anticipative yaw and pitch controllers allow to gain in charge factor as wind turbines can produce under more turbulent wind conditions.

However, intermediate processing steps are mandatory to reach a robust and efficient control law. The first step is to use the radial LiDAR raw measurements to estimate what force is really applied on the rotor plane. This task needs adapted signal processing and reconstruction algorithms.

The second one is to interpret these estimates to determine the best foreseen value for the control actuators to reduce the mechanical solicitation while maintaining the power production requirements.
This paper presents innovative wind field filtering and reconstruction strategies to retrieve significant wind information from the nacelle LiDAR real-time raw data. The collected experimental data and the exposed results have been produced in the context of a collaborative experimental project, SMARTEOLE, which involves IFPEN, LEOSPHERE, MAIA EOLIS and Orleans PRISME laboratory.

In addition, the short-term forecast knowledge of the rotor effective wind speed is used to further develop a nonlinear two stage control strategy, previously implemented at IFPEN and presented in [11]. It results in an anticipating control approach, that takes into account actuators dynamics in order to reach true “on-time” blade pitch angle positioning. Performance indicators are obtained from an onshore FAST/SIMULINK platform, designed to be representative of MAIA EOLIS operated onshore wind turbines, which are SENVION MM82.

2. SMARTEOLE experiment setup

As illustrated below, the setup consists in an industrial SENVION MM82 turbine instrumented for the project. The main objective of this project consists in optimizing wind turbine costs by reducing wind-induced mechanical stress. The means are LiDAR based alert indicators and pitch/yaw control laws. Wind farm optimization is also addressed. Figure 1 illustrates a part of the instrumentation, including a new nacelle 5-beams LiDAR manufactured by LEOSPHERE and an IFPEN pitch control unit prototype, designed to embed real-time reconstruction and control algorithms. LiDAR measurements and lines of sight are also represented.

Figure 1: SMARTEOLE setup

A first processing step of wind turbine and LiDAR acquisitions allows to get a realistic description of the power curve and performance coefficient, as shown in Figure 2. These information are required preliminaries to design pitch control strategy and in this case are fully realized using only a Lidar
device. This allows to plot the actual power law with undisturbed flow ahead of the turbine instead of using usual anemometer filtered data.

An inclinometer is also integrated in the control unit hardware, to integrate a vibration and stress indicator for the developed control law.

![SmartEole wind turbine power curve](image1)

**Figure 2**: SMARTEOLE experimental data (acquisition period: 2015 November 28th)

### 3. From LiDAR measurement to rotor wind estimation

Extracting wind speed and direction in a point of space ahead of the wind turbine present many technical issues, caused in particular by:

- LiDAR spatial transfer function,
- Measurement noise,
- Beam projections,
- Induction zone effects.

Induction factor quantifies the decrease of air velocity caused by the rotor blocking effect. Thus wind speed at rotor plane is noticeably lower than 200m upstream.

A signal processing stage has been developed to compensate for these drawbacks. It provides a model-based estimation of the beam measurement, based on wind spectral and spatial characteristics. It also takes into account the pulsed LiDAR spatial convolution effect. This approach is auto-adaptive and does not require any specific site calibration. This strategy is designed with a Wiener filter, whose implementation and performances were previously described in [12]. It is used here as a pre-processing component for wind field reconstruction. Reconstruction approach is also model based, as it mixes LiDAR filtered measurements with a calibrated induction zone map, the wind power law from IEC norm [13], and calibrated spatial and temporal coherence.

#### 3.1 Induction zone estimation

Rotor blocking effect can be observed in experimental data extracted from nacelle LiDAR measurements. Based on these data, a mapped induction factor, depending on distance upstream nacelle and on wind speed, has been designed. Measurements are fed into an approximant algorithm that elaborates the map with a least squares optimization method. As illustrated on Figure 3, a coherent and realistic induction factor mapping is obtained. As expected the closer from the rotor plan it gets, the higher is the induction factor (induction factor of 0 to represent no wind speed decrease). It is interesting to note that a correlation of the induction effect appears as a function of the mean wind speed. Induction effects are reduced for larger wind speeds. The map is produced by the processing of a relevant extraction of the measurements database (typically one day of data with a wide enough
variation of mean wind speed). As expected, the obtained map can be applied on the other acquisition
days. This induction zone model provides a relevant input for wind reconstruction and for LiDAR
measurements robustness and data availability improvement.

![Induction attenuation factor](image)

**Figure 3:** Wind turbine induction zone map from reconstructed longitudinal wind component

### 3.2 Wind field reconstruction

The use of LiDAR beams undergoes the so called Cyclops dilemma, as only a projection of the
wind vector onto the beam axis is measured. Recovering the complete directional information of the
wind needs additional inputs, which are the other beam measurements. Combining beam
measurements pointing to separate and noticeably distant areas, and at non-simultaneous acquisition
dates, needs strong assumptions on wind homogeneity in space and time:
- steady flow across the rotor plane [14]
- measurements along the beams considered acquired at the same time

These hypotheses may not be realistic enough to obtain accurate representative wind speed and
direction estimates.

The reconstruction strategy exposed here, currently in validation stage, aims at relaxing those
hypotheses by means of an adapted wind model, coming from power law considerations and induction
zone effects quantification. In addition, linear least squares reconstruction is considered locally with
the determination of measurements subsets of beams and ranges (i.e. distance to the nacelle), around
the areas of interest.

Several approaches are currently being tested to build a coherent and realistic grid estimation
of the incoming wind field. The intermediates results shown on figure 4 come from a strategy
implemented as a weighted recursive least square problem, solved by the minimization of a particular
cost function. The design of this cost function considers temporal and spatial coherence of the wind,
quality of LiDAR measurements and a power law. A specific effort in implementation has been made
to satisfy real-time constraints, in order to embed this strategy onboard blade pitch control unit.
Figure 4: Wind field estimation upstream the 5-beams nacelle LiDAR

Figure 4 emphasizes on the obtained wind field grid, at a specific time, from 2015 November 28th acquired data. Left diagram represents a view from above [X-Y] of the LiDAR radial measurements (red arrows), and reconstructed wind vectors at different altitudes, (superimposed arrows for which colors depend on the distance to nacelle). Right diagram is a view from [X-Z] of the same measurements and reconstructed vectors. These diagrams allow qualitative verification of the spatial and temporal coherence of the whole stream estimation. In fact left diagram shows wind shear propagation and attenuation due to rotor blocking effect.

Figure 5: Relative error on wind reconstruction, comparing measurements to estimates projected on corresponding lines of sight

Implementation has been validated by comparing wind estimates projection at measured locations (line of sight and range) with measurements. As exposed on figure 5, estimates are properly correlated with measurements. For a wider range of validation, the whole reconstruction strategy is being tested on generated winds from CFD tools, and on experimental data. An experimental cross validation campaign is also in progress on SMARTOLE site. A Leosphere “Windcube” vertical profiler has been placed 200m ahead the nacelle, in the preponderant wind direction, so that Nacelle-LiDAR reconstructed wind can be compared with Windcube measurements. Outputs cannot be consolidated yet as these steps are in progress.
Figure 6: TFH and induction zone effect observed on reconstructed wind field

As illustrated on figure 6, Taylor Frozen Hypothesis (TFH) assumption is partly verified, as induction zone weighting and wind turbulences have to be taken into account. One can see that from one measurement distance to another the time delay appears to stay in the same range which validate the temporal propagation nature of the wind field. On top of that, when getting closer to the rotor plan, the wind speed tends to decrease due to the induction zone effect. These outputs consolidate recently proposed methods to avoid or relax TFH assumption [15-16]. Future works will consist in adapting TFH hypothesis thanks to LiDAR extracted parameters.

These promising intermediate results permit to reconstruct the wind field at the rotor plane. Next step is the estimation and prediction of efforts and loads applied on the whole blade surface. This allows for much more precise estimation of load factor, synthesis of alert indicators, better management of the wind turbine setpoints, increased life expectancy and reduced maintenance costs.

As the project is currently in acquisition stage, the designed blade pitch control strategy explained in next section was validated on simulation.

4. Innovative control design for power maximization and loads mitigation

In [11], a new control strategy developed at IFPEN has been presented and tested in simulation. The strategy consists in a two-stage control. The first stage provides a nonlinear feedforward for rotor speed regulation along with a nonlinear dynamic feedback, that improves the robustness of the control. The second stage control aims at minimizing the tower fatigue on the basis of the solution of an LQR problem.

The control strategy has been tested using the “Fatigue, Aerodynamics, Structures and Turbulence” (FAST) code developed by NREL [17]. Simulation results showed a significant tower fatigue reduction, up to 50% for certain wind conditions, for both side-to-side and fore-after direction.

In spite of good performance of the proposed method, the effectiveness of its practical implementation is limited by the pitch actuators dynamics. In this section, the control strategy is further improved in order to include these dynamics in the control design step, by employing the LiDAR sensor to anticipate the incoming wind.

Assume that the pitch actuator dynamics are approximated by a first-order system with a time constant \( \tau \), i.e., in a discrete time framework,

\[
\theta(k + 1) = (1 - \tau \Delta T)\theta(k) + \Delta Tu(k + 1)
\]
where $u$ is control signal, $\theta$ is the blade pitch angle and $\Delta T$ is the sampling time.

Considering the incoming wind prediction provided by the reconstruction strategy, the goal is to ensure that the effective blade pitch angle $\theta$ remains as close as possible to the pitch angle set-point $\theta_{\text{target}}$ for every instant from $k$ to $k+N$, where the prediction horizon $N$ is chosen accordingly to the advance on the incoming wind speed given by the LiDAR. To achieve this result, the following cost function is used:

$$J = \sum_{i=0}^{N-1} q_i (\theta(k+i+1) - \theta_{\text{target}}(k+i+1))^2 + r_i u(k+i)^2$$

(2)

where $q_i \geq 0$ and $r_i > 0$, $i = 0, 1, ..., N - 1$, are tuning parameters.

It is well known [3] that the solution that minimizes the cost function $J$, subject to the dynamic constraints (1) is

$$u(k) = K\theta(k) + F\Theta(k)$$

(3)

with

$$\Theta(k) = [\theta_{\text{target}}(k+1), ..., \theta_{\text{target}}(k+N)]^T$$

(4)

and $K \in \mathbb{R}$, $F \in \mathbb{R}^{1 \times N}$ functions of $\tau$, $\Delta T$, $q_i$ and $r_i$. The vector $\Theta$ is computed based on the LiDAR wind speed measurements in the time interval between $k$ to $k+N$.

To validate the proposed control law the FAST simulation tool is used. With the analysis of experimental data collected during the test campaigns of SMARTOLE collaborative project, the 2MW wind turbine operated by MAIA EOLIS has been modeled and integrated in FAST environment. Aerodynamic, electrical and mechanical models have been dimensioned and calibrated.

The wind inflow used in the simulation environment is obtained from experimental data and consists of a 1200s data set of full-field turbulent wind. As pointed out, the proposed control strategy is based on LiDAR wind measurements. In addition, the adaptive Wiener filter [12] is used to improve the LiDAR measurements, as mentioned in the previous section.

Figure 7 compares wind at the rotor plane, LiDAR measurement and Wiener Filter output at the same location. FAST wind input is obtained with the experimental acquisitions (anemometer wind speed and LiDAR measures). The gain of the filter deconvolution effect can be clearly seen (higher frequency information retrieved).
For performance measurement, three control scenarios are compared. The two-stage control strategy is firstly compared to a classical feedback approach, which is a rotor speed regulation by means of a gain scheduling PID controller. Then both are compared to the enhanced version of the two-stage control, which includes the pitch actuator response time compensation based on the LiDAR prediction of the incoming wind speed. Shown results are under rated conditions, at 2 MW stabilized active power. Figures 8-10 show comparisons of the results.

Figure 8 left diagram presents the performance of two-stage control law, with and without actuators compensation. Anticipation of actuator’s time constant can be observed in pitch angle measurement. The actuator acts earlier with the integrated compensation. Figure 7 right diagram shows the benefits on tower oscillation reduction, as tower top fore-after (FA) deflection amplitude is noticeably reduced.

In Figure 9, two stage control performance is a bit enhanced with pitch actuator compensation, but in a less noticeable way, for rotor speed and generator torque. Figure 10 highlights that maximum moment on the base tower are damped more effectively. A decrease of 37 % is observed for the tower fore-after moment.
The results summarized in Table 1 confirm the tower-top fore-after and the rotor speed fatigue reduction obtained in simulation with the proposed control strategy. Accordingly to application of Miner’s rule, the fatigue is computed with the rain-flow counting method as

\[
\text{Fatigue}_v = \sum (\text{Number of cycles})(\text{Cycles amplitude})^{3.5}
\]  

Table 1 Simulation results: fatigue on tower displacement and fatigue on Rotor. A classical gain scheduling PID control is compared to the two-stage control strategy and to the two-stage control with the pitch actuators compensation control strategy.

<table>
<thead>
<tr>
<th></th>
<th>PID</th>
<th>STAGE 2</th>
<th>STAGE 2 and ACTUATORS COMPENS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOWER-TOP FA</td>
<td>100%</td>
<td>72.9%</td>
<td>35.2%</td>
</tr>
<tr>
<td>ROTOR</td>
<td>100%</td>
<td>32.5%</td>
<td>24.7%</td>
</tr>
</tbody>
</table>

Compared to a classical PID feedback regulation, the two-stage control law allows a fatigue reduction on the tower displacement of about 27%. When the actuators compensation is included in the control strategy, a gain of about 65% is obtained. Similarly, the rotor fatigue is reduced of 63% with the two-stage control and of about 75% if the actuators dynamics are taken into account in the control strategy design. The rotor fatigue metric correspond to the Miner’s rule applied to variation of the rotor speed around the rated speed.

Simulations performed in this paper are not intended to validate the control strategy for all wind conditions that can be experienced by the turbine. A second validation step will be to validate the proposed approach on design load cases defined in IEC (DLC 1.x regarding power production wind conditions) that takes into account ultimate and fatigue load calculations.

5. Conclusions and perspectives

By exploiting a previously developed strategy for LiDAR radial measurement filtering, an innovative work was presented in this paper regarding wind field reconstruction. Intermediate results on experimental data are promising. An additional wind measurement system is about to be installed on the SMARTEOLE experimental setup, so that wind speed reconstruction can be cross-validated.
This measurement device is a LiDAR vertical profiler (Windcube), positioned on the ground close to the wind turbine.

There are several perspectives of exploitation for the outputs of the wind field reconstruction. One of them has been addressed in this paper. It consists in the enhancement of an existing control strategy with the anticipation of the pitch actuators dynamics. In fact, having a precise and realistic spatial and temporal estimation of the incoming wind allows to anticipate even the time response of the pitch actuator with a feedforward based control approach. As shown in the results, the strategy brings noticeable benefits quantified in fatigue and extreme loads reduction.

Next step is the validation of the whole strategy, including filtering, reconstruction, loads diagnostics and pitch control, on a full simulation suite on the SMARTEOLE developed platform based on design load cases defined in IEC standard. Then, the final deployment of the validated processing and control strategies into the “WiSEBox” control unit, already on site, will be achieved for real testing, provided that pitch setpoint external input is made possible for the control component.

Acknowledgements and References
The present work is funded by the national project SMARTEOLE (ANR-14-CE05-0034)


