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Identification in Closed Loop Operation of Models for Collective Pitch Robust Controller Design.

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Key words

Wind Turbine, pitch loop, closed loop identification, robust control.

Abstract

In order to achieve load reduction and power optimization, wind turbine controllers design requires the availability of reliable control oriented linear models. These are needed for model based controller design. Model identification of wind turbine while operating in closed loop is an appropriate solution which has recently shown its capabilities when linear time invariant controllers and complicated control structures are present. However, the collective pitch control loop, one of the most important wind turbine loops, uses non linear controllers. Typically, this nonlinear controller is a combination of a linear controller and a gain scheduling. This paper presents a new algorithm for identification in closed loop operation which allows the use of this kind of nonlinear controllers. The algorithm is applied for identification the collective pitch demand to generator speed of a wind turbine at various operating points. The obtained models are presented and discussed from a control point of view. The validity of these models is illustrated by their use for the design of a linear fix robust controller. The performance based on simulation data of this linear controller is similar to that obtained with simulations based on a linear controller with gain scheduling but its design and implementation is much simpler.

List of Acronyms

WT – wind turbine.
COLM - control oriented linear models.
LTI – linear time invariant.
CLOE – closed loop output error.
R – Rotor diameter.
V – Wind speed.
 λ – Tip Speed Ratio.
 ρ – air density.
C_p – Power coefficient.
C_l – Aerodynamical lift coefficient.
 Ω – Generator speed.
 $\hat{\Omega}$ – Estimated generator speed.
 β – Collective pitch angle demand.
 $\hat{\beta}$ – Estimated collective pitch angle demand.
 ε^0 – Predictor error a priori.
 ε – Predictor error.
e – White noise.
ru – Input Excitation signal.
 θ – vector of parameters to be estimated.
 Φ – measurements vector.
R/S – Linear controller of numerator R, and denominator S.
B/A – Linear transfer function, with numerator B and denominator A.
PI – Proportional integral controller.
PID – proportional integral derivative controller.

N/M – linear filter with numerator N, and denominator M.

1P – disturbance which corresponds to the frequency of one rotor revolution time.

nP – disturbances at n times the frequency 1P.

MIMO – multi inputs, multi outputs system.

$A(q^{-1}), B(q^{-1}), C(q^{-1}), D(q^{-1}), R(q^{-1}), S(q^{-1})$ – polynomials in the delay operator q^{-1} ($q^{-1}y(t) = y(t-1)$).

$A(z^{-1}), B(z^{-1}), C(z^{-1}), D(z^{-1}), R(z^{-1}), S(z^{-1})$ – polynomials in the complex variable z^{-1} .

t – normalized sampling time ($= t/T_s$ where T_s is the sampling period).

NLC – Non Linear Controller.

PAA – Parameter Adaptation Algorithm.

1. Introduction

Better models leads to better controllers. This is a very well known axiom in the Control Engineering World. It is also well known that, for control purposes, the best model for control design is not necessary the most complicated and detailed one. Wind Turbines (WT) control is not an exception. Actually, for control design purposes, the most used representation of a system is through a set of linear time invariant (LTI) models. Of course, more sophisticated non linear models are needed for control testing, but not for controller design.

It is well known, [1] to [11] and others, that control loops and its parameters are critical from generated loads point of view. Offshore challenges like uncertainty, size and power increase, makes the control even more important in terms of loads and stabilization. The linear models in several points of operation, is the basic tool for controller design. Tuning of control loop parameters is a relatively well solved problem in the wind sector, [1] to [13], since linear models based on linearization of nonlinear aeroelastic codes, [14] to [16], are generally used. However, it seems to be very common that control parameters tuned during WT design, and used for the certification process, do not exactly correspond to those finally implemented in the real WT, [10]. Then, the pertinence of these linearized models can be criticized since in many occasions the control parameters are not subsequently used in the real WT. Then, one question appears. How are these controllers tuned in real WT? Most of the times, the final on site tuning is based on the experience of the Control Engineer who proceeds according to rules of thumb or on a trial and error basis. This approach, in many situations, makes the controller tuning, very time consuming, inaccurate and unable to cope with the nonlinear characteristics of the whole system. Even more, there is absolutely not evidence about the robustness of these tuned controllers. Therefore, there is a need for obtaining relevant and accurate models on site which can effectively be used for controller tuning.

Consequently, although big efforts in modelling WT were done, [17] to [28] among other references, as well as for getting linearized models, [14] to [16], the search of a procedure to obtain reliable control oriented linear models (COLM) for control design seems a pertinent research task. Open loop system identification techniques, [29], can be used for obtaining on site realistic COLM. Open loop identification is probably the most extended technique for obtaining empirical models from experimental data. This technique is well known and has proven its goodness in a number of fields and applications. However, this technique should be avoided for the extraction of wind turbines empirical model's in practice for different reasons which are commented in section 3.

Different approaches have been tried in the frame of WT identification, but they usually look for different purposes. In [30], an experimental approach for finding aero elastic damping is introduced. In [31] and [32], the identification is divided between a linear model, for drive train identification, and non-linear model for the aerodynamical effects, with extra measurements. In [33], a full transfer function from torque demand to generator speed is obtained based on open loop identification algorithms.

The use of a controller during the execution of identification experiments warranties not only the stability and integrity of the WT, but also operation around a fixed operational point. Therefore it is important to study the possibility of WT identification in closed loop operation, [34] to [38]. Using these new techniques of identification in closed loop is probably the best option for solving the problems coming from the nature of the Wind Turbines and open loop identification. CLOE algorithms, [37] [38], have shown their capabilities for extracting reliable linear models for control design purposes in different application while the system is operated in closed loop, [39]. These algorithms are however designed to operate only in the presence of LTI controllers.

In variable speed - variable pitch WT, the known as Collective Pitch Control loop regulates the generator speed when rated power is reached, figure 1. This loop usually has a non linear structure. One of the most common approaches is to use a LTI controller with a gain, whose value depends on the state of the system, known as “gain scheduling”. So, appropriate algorithms have to be developed in order to do identification in closed loop operation in the presence of this kind of nonlinear controllers.

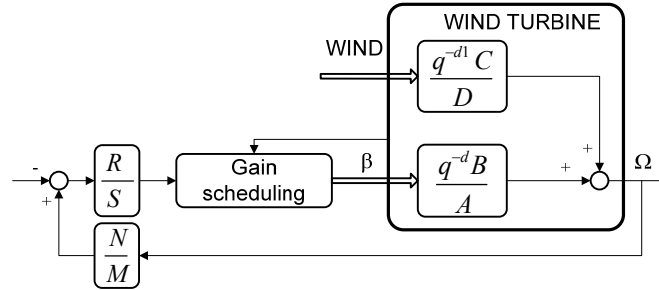


Figure 1. Classical Collective Pitch Control Loop representation

The first objective of the present paper is to develop an algorithm for plant model identification in closed loop operation when the used controller is nonlinear.

The second objective of the present paper is to show how this new algorithm can be used to obtain a set of COLM for representing the dynamics between the collective pitch demand and the measured generator speed, around various operating points. Of course it is assumed linear behaviour of the system during the experiments developed in Bladed, [14]. The experimental protocol designed uses a linear controller with gain scheduling, however. The authors consider that this is the most realistic and safe approach for WT commissioning, since these controllers are available from the WT design process.

The third objective of the paper is to analyse the properties of the various identified models. It will be shown that their properties vary drastically with the wind speed. These models present zeros which moves from outside the unit to inside the unit circle, while wind speed increases.

Since a set of identified COLM around various point of operation are available, at least two approaches are possible to design the pitch controller:

- Design a nonlinear controller with gain scheduling, i.e., use the identified models and keep the control structure concept.
- Design a single fix robust linear controller for the collective pitch control loop, which achieves the desired performances, for all the identified control oriented linear models.

Then, the fourth objective of the paper is to show that, indeed, it is possible to replace the linear controller with gain scheduling, by a single fix linear controller for the same level of performance, provided that a set of reliable identified COLM are available and a robust controller design technique is used. A comparative simulation of the WT, with wind speeds from 8m/s to 22m/s, demonstrates the equivalent performance in terms of rotor speed and collective pitch demand for both controllers. In addition for the fix controller the robust stability is guaranteed.

The paper is organized as follows: In section II, a brief review of physical model and the control of generator speed in rated power by the collective pitch is presented. In section III, the linearized models coming from aeroelastic codes are evaluated, the state of the art on identification is commented and the new algorithm of CLOE family for the identification in closed loop operation in the presence of linear controller with gain scheduling is presented. In section IV, the simulations carried on for obtaining data for closed loop identification are presented. Section V presents the obtained models and the validation through a control performance on a realistic simulation. Concluding remarks and future direction of research are in Section VI.

2. Collective Pitch Control Loop

2.1. Collective Pitch Demand to Generator Speed, physical system overview.

The dynamic from collective pitch demand to generator speed is complex. It has been extensively studied, [2] and [17] to [21]. Many important details should be taken into account, like aerodynamics, blades and tower's structural dynamics, drive train... Many efforts in describing the physics were done in these fields. Here, only some remarks concerning the main control problems will be briefly commented.

There exists a very well known nonlinear relationship between the extracted power, P , from the wind and the wind speed, V . Such relation is given in eq.1, where ρ is the air density. The extracted power depends linearly on the area of the rotor characterized by the rotor's radius, R . The term C_p in eq.1 deals with the characterization of the aerodynamical performance of the rotor blades. Taking into account that common rated wind speeds are between 10 - 12 m/s, and that common cut-out wind speeds are between 20 and 30 m/s, there is an important non-linear effect that should be taken into account by the controller in this range of wind speeds.

$$P = \frac{1}{2} \rho \pi R^2 V^3 C_p(\lambda, \beta) \quad (1)$$

Active blade pitch control can be done in two opposite directions: to stall or to feathering. The most popular concept is pitching to feathering. In this case, for the operating pitch angle range there is a linear relation between the angle of attack and the lift coefficient, C_l , see figure 2. If the pitch angle increases, the angle of attack decreases. If the wind speed increases, the angle of attack increases. Normally, the control loop is designed in order to operate at this linear range, avoiding problems coming from stall operating at higher angles of attack, where higher loads and uncertainties appear and the linear relationship disappears, [17].

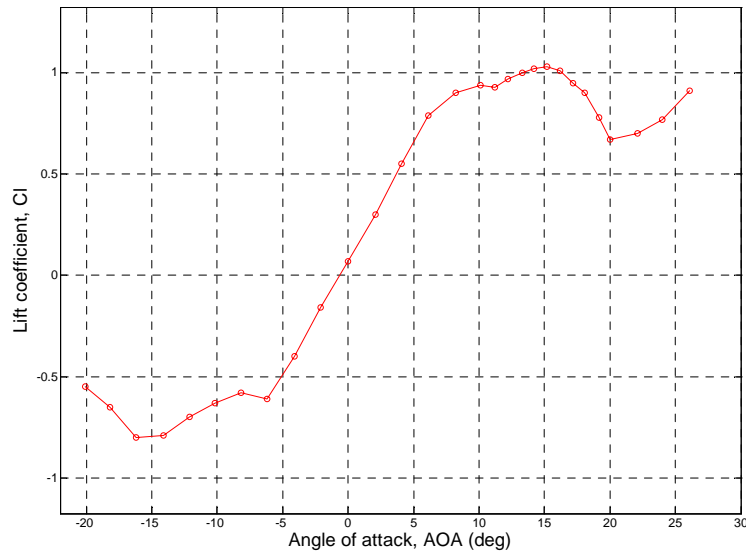


Figure 2. C_l curve for S809, Reynolds 1.000.000. Source NREL

Another crucial effect, in the collective pitch demand to generator speed dynamics, is the coupling of the regulation speed loop with blades and tower's structural dynamics. Changing pitch angle causes variations in both aerodynamical torque and thrust. This means a direct coupling between the rotor speed excursion and the structural dynamics. Torque variations may come from wind variations, but also from blades and tower motions induced by the aerodynamical thrust changes. This well known phenomenon may introduce non minimum phase behaviour in the control loop. This effect depends on the mass distribution and the operational conditions, [17],[20].

Other features of the collective pitch demand loop, like wind shear, gravity loads, wind turbulence, tower shadow or imbalanced rotor should also be taken into account. These disturbances are related with the time per revolution of the rotor, leading to the well known nP disturbances. The effects of these disturbances on the controlled output are very powerful. Actually it has been shown, [41], that this effect on the output is sometimes more powerful than the effect of the controlled input demand. The effect of these disturbances, when using a simple PI controller, can cause unwanted activity of the pitch actuator at these frequencies. This can cause an amplification of these disturbances, which can destabilize the turbine if they are not taken into account in the controller loop design.

Note also that the undamped torsion mode of the drive train is always present in the collective pitch dynamics in open loop. However this is usually damped in the torque loop, [43]. So if this torsion mode is correctly damped, it is invisible in the collective pitch control loop.

2.2. Classical Collective Pitch Control Algorithm

For variable speed WT configuration, the collective pitch control loop is active at medium and high wind speeds. The main objective of the collective pitch loop is to modify the pitch angle of the blades in order to regulate the rotor speed, while trying to reduce mechanical loads.

The most extended solution to regulate the generator speed at rated power with collective pitch demand is shown in figure 1. A polynomial controller, R/S , combined with a Gain Scheduling is commonly used. According to the dominant dynamics, low order controllers like PI or PID are very popular. This could be correct because the dynamic of the rotor speed is dominated by its huge inertia at lower frequencies. In addition, PI and PID are very well known controllers, which can be tuned on site, although probably their tuning is far from being optimal.

However, a simple PID cannot deal with the non-linear aerodynamical effects coming from the aerodynamics, eq.1. There is certainly an important change in the gain of the collective pitch to generator speed model coming from the wind speed variations. In addition, the PID cannot take care of the non linearities coming from the coupling between aerodynamics and structural dynamics. These phenomena are important since they oblige to reduce controller's bandwidth. Then, simple controllers like PI or PID are modified in order to accommodate these nonlinearities. A common solution is to implement a gain scheduling based on indirect measurements of wind speed, [1] [2] [7]. The gain scheduling introduces a non-linear behaviour to the controller.

It is also very common to use filters in the feedback loop of the collective pitch control loop. These filters, summarized in figure 1 as N/M , may have different purposes. Avoiding the excitation by some disturbances or reducing collective pitch demand activity at high frequencies, are typical objectives of these filters.

In Figure 1, the plant model is defined as the transfer operator:

$$\frac{\text{Measured Generator Speed}}{\text{Collective Pitch Demand}} = \frac{B(q^{-1})}{A(q^{-1})} = \frac{q^{-d} [b_0 + b_1 q^{-1} + \dots + b_{nb} q^{-nb}]}{1 + a_1 q^{-1} + \dots + a_{na} q^{-na}} \quad (2)$$

where:

- d represents the integer delay between the pitch actuation and the generator speed (in terms of sampling periods).
- $B(q^{-1})$ and $A(q^{-1})$ represents the numerator and denominator of the collective pitch to generator speed model¹.

In figure 1 is also represented the full collective pitch control loop where:

- *Gain Scheduling* represents the non linear part of the controller.
- $R(q^{-1})$ and $S(q^{-1})$ represents the numerator and denominator of the linear part of the controller.
- $N(q^{-1})$ and $M(q^{-1})$ represents the numerator and denominator of the filters in the feedback loop.
- dI , $C(q^{-1})$ and $D(q^{-1})$ represents the disturbance model of the pitch loop.
- Ω is the measured generator speed
- β is the collective pitch demand
- The feedback loop uses positive feedback, since the system has negative gain

The collective pitch control loop presented is a commonly used solution for regulating generator speed at rated power. Although this control scheme can be more complicated, this one is representative enough of the actual state of the art².

¹ q^{-1} is the unit delay operator: $q^{-1}y(t)=y(t-1)$

² More complicated non linear controllers or multivariable control schemes for reducing or alleviating some of the difficulties commented in section (2.1) has been proposed. These more advanced control schemes are out of the scope of this paper.

The model of the system changes with wind conditions. Then, models for various operation points are needed to have a good representation of the WT dynamics at different wind speed conditions. Therefore, an identification of these models is necessary. This has to be done in closed loop operation, in the presence of the pre-designed controller with gain scheduling.

3. CLOE identification algorithm in the presence of nonlinear controllers

3.1. Linearized models coming from WT aeroelastic code.

The linearized models obtained from aeroelastic codes were a significant advance for understanding the main control loop dynamics and couplings. Of course, they help in the design process of model based controllers. These models have shown a number of drawbacks, however:

- The operational point for these models, constant wind speed for every point of the rotor area, may be very far from the real operational conditions. This is especially true for WT operating in complex terrains. Effects like wind shear, turbulence or tower shadow also moves the real operating condition far from constant wind speed for the whole rotor, [14] to [16].
- The routines which deliver the models do not always converge to a periodic state solution, which is commonly used as operating point for obtaining the linearized models.
- The high order of the obtained models, (between 30 and 40) is unnecessary high for describing the main plant dynamics for control design purposes.
- It is common that non observable modes appear in the linearized models, which in addition makes the models numerically ill conditioned.
- Numerical errors caused by linearization techniques introduce unrealistic dynamics, especially at low frequencies. This is especially noticeable in phase plots, and makes the stability analysis of the designed controllers unreliable.
- The modelling errors on aeroelastic codes or wrong parameterization of the models can enlarge the gap between theoretical models and the real dynamic behaviour of the WT.

A consequence of the above mentioned problems is that, sometimes, the controller designed based on these linearized models do not provide the expected performance on real WT. The consequences in practice are:

- i. A new controller should be designed in order to stabilize the real WT.

If the controller designed with the linearized models doesn't work properly, no matter which the reason is, this controller needs to be redesigned. Sometimes, small changes in the parameters need to be done, but in a number of situations, important deviations from the original controller's parameters may occur, [10].

- ii. Model based controller design is no more possible for the real operating controller.

As long as a reliable model is not available, the redesign of the controller is commonly based on the expertise of the control engineer, who usually applies rules of thumb. This can be very time consuming and introduce many doubts about the optimality or robustness of the controller.

In addition, it is not possible to compute the basic robustness margins, which allow to assess the robustness of the controller, without a reliable model. Then, it is not possible to assess the robustness of the used controller. This is probably the major problem, since this may drive the system to instability under certain circumstances, like disturbances, non linear effects, or uncertainties.

- iii. The controller used for certification of WT loads, and consequently used in the mechanical design of each component is no more used in real WT.

Certification loads are computed for 20 years of WT operation for both extreme and fatigue loads. Fatigue loads, where control plays an important role, is strongly affected by a wrong controller parameterization. If there is an important deviation from the performance of the certified controller, this may translate into a deviation between estimated –certified – loads and real operating loads. This is a drawback from the long term WT integrity point of view. Even more, this means that there is no certainty about the loads which will be generated in the WT.

From these drawbacks, it can be concluded that the linearized models coming from WT simulators are a good qualitative representation of the WT dynamics, although they are not an accurate enough representation of the real operating WT dynamics. Then, they cannot be used for in site control tuning if the designed controlled fails on the real WT. One also concludes that a procedure is needed to obtain COLM of each WT, in order to obtain a robust controller which will approach an optimal behaviour.

3.2. State of the art for obtaining linear models from experimental data for WT

In many fields, the most extended technique for obtaining linear models for control purposes is the open loop system identification, [29]. However, these techniques are too risky and should be avoided in the frame of WT since:

- The source of energy which governs the WT, the wind, is not under control. Then it is hard to set an open loop identification experiment.
- Since the wind speed is not under control, it is not possible to fix an operating point representative of the real operating condition of the WT.
- Operating a wind turbine in open loop can be very risky, create excessive loads, existing the possibility WT instability, or in the worst case, can get the WT to collapse.

In order to avoid some of these inconveniences and restrictions, the identification of WT in closed loop operation has been considered, [35] to [38].

Identification in closed loop operation was initially discarded in the eighties. The available algorithms for open loop identification were unable to produce relevant models when used in close loop operation. These algorithms suppose that there is no correlation between the input and output data. However, if the experimental data are obtained in closed loop operation, there is a strong correlation between the measured noise and the real input to the plant. A number of “indirect” techniques have been developed in order to try to overcome this correlation between input and output data. One of these use the “instrumental variable”³ concept, and require several steps. This technique was used by [33] during the nineties in the frame of Wind Turbine identification.

Newer developments for identification in closed loop operation opened the possibility to obtain relevant COLM in one step, from experimental data acquired in closed loop operation. WT identification, when operating in closed loop, has been studied in the last years, and different approaches have been proposed.

In [40] a linear parameter varying identification on repetitive sequences and subspace identification in closed loop has been applied to a WT. However quite long experiments, 50 minutes, are required, which may be a serious problem in practice. A different approach for identify WT in closed loop operation was presented in [42], where CLOE algorithms and heavy filtering were used for constant wind speeds. In [43], the limitation of constant wind speed was removed. CLOE algorithms succeed to identify the transfer function between torque demand to measured generator speed, in the presence of three dimensional turbulent wind speed. This solution was able to identify the WT model in the presence of linear controllers, filters, and also linear drive train dampers.

This paper is an extension of the methodology used in [42] and [43] to the collective pitch control loop. The existing CLOE algorithms are not applicable since in the collective pitch control loop one often uses a nonlinear controller. In this paper, a new CLOE algorithm is proposed. This allows the identification of the transfer operator for collective pitch demand to measured generator speed, when a non linear controller is being used in the loop. Of course, the identification is made possible in the presence of three dimensional turbulence wind speed, and without the measurement of the wind.

³ An « instrumental variable » is an auxiliary variable which is correlated with the true variable and uncorrelated with the noise.

3.3. The new identification algorithm

The objective of CLOE algorithms is to identify a plant model that, in feedback with the actual controller, gives a closed loop transfer function as close as possible to the real operating one. The algorithm developed for the identification of the collective pitch control loop, shown in figure 3, is an extension of CLOE family algorithms for this case of nonlinear controller.

This approach is applied to the collective pitch control loop of a WT. The objective is to get a transfer function from the collective pitch demand to generator speed, based on experimental data, while operating in closed loop. Suppose the real generated speed, Ω , and the estimated generator speed, $\hat{\Omega}$, are given by, eq. 3 and eq. 4, where β is the collective pitch angle demand, e is white noise and ε the predicted error:

$$\Omega(t) = \frac{z^{-d} B(q^{-1})}{A(q^{-1})} \beta(t) + \frac{z^{-d1} C(q^{-1})}{D(q^{-1})} e(t+1) \quad (3)$$

$$\hat{\Omega}(t) = \frac{z^{-d} \hat{B}(q^{-1})}{\hat{A}(q^{-1})} \hat{\beta}(t) + \frac{z^{-d1} \hat{C}(q^{-1})}{\hat{D}(q^{-1})} \varepsilon(t) \quad (4)$$

where:

$$A(q^{-1}) = 1 + a_1 q^{-1} + \dots + a_{nA} q^{-nA} \quad (5)$$

$$B(q^{-1}) = b_1 q^{-1} + \dots + b_{nB} q^{-nB} \quad (6)$$

$$\hat{A}(q^{-1}) = 1 + \hat{a}_1 q^{-1} + \dots + \hat{a}_{nA} q^{-nA} \quad (7)$$

$$\hat{B}(q^{-1}) = \hat{b}_1 q^{-1} + \dots + \hat{b}_{nB} q^{-nB} \quad (8)$$

characterize the real and estimated models of the transfer function between collective pitch demand and generator speed. The real measured output of the system, eq.3, and the estimated plant output, eq.4, are used to compute the closed loop error, $\varepsilon_{cl} = \Omega - \hat{\Omega}$, see figure 3.

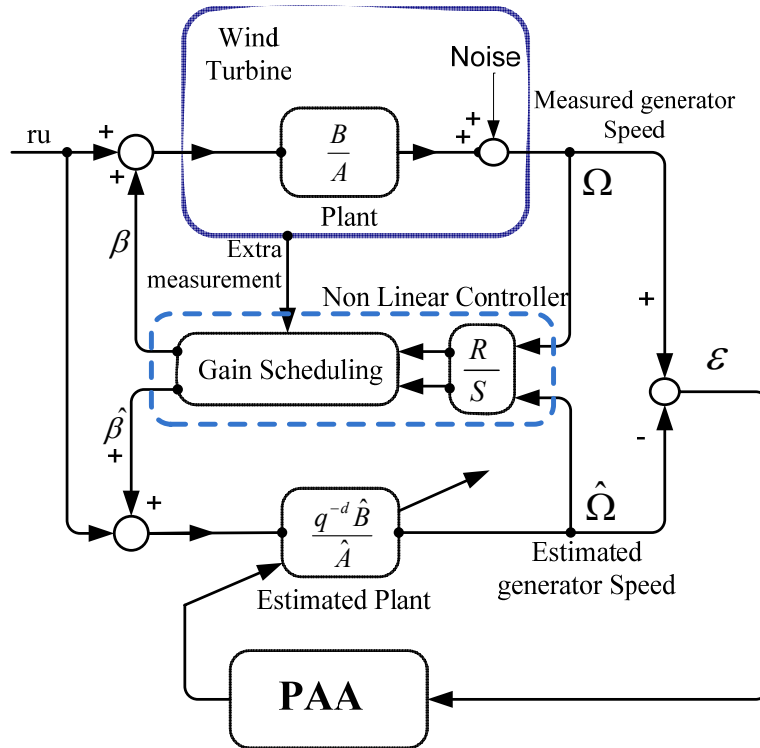


Figure 3. The new closed loop identification algorithm scheme used for systems controlled with non linear time varying controller

The input excitation signal can be applied in the reference signal or at the output of the controller. Since this is a regulation problem, the input excitation signal, r_w , is applied at the output of the controller, see figure 3. The estimated collective pitch demand, and the real collective pitch demand are both computed with the real operating nonlinear controller. The first gets into the estimated model, and the second gets into the real operating system. The closed loop error, ε_{cl} , is used by the Parameter Adaptation Algorithm (PAA), which recursively estimates the parameters of the estimated plant model.

The estimated parameters can be organized in a vector of parameters θ , to be estimated. The measurements can also be arranged in a measurements vector, Φ , and used in the PAA. The PAA algorithm is defined by equations 9 to 12, a recursive algorithm inspired by the recursive least squares. Here, ε^0_{cl} is the a priori prediction error, this means it is computed before measurement for time $t+1$ is available. The prediction error ε_{cl} is computed once this measurement is available. F is a gain, and gives and idea of the magnitude of the change in the estimation of the parameters, and can be manipulated in order to weight the measurements in time by different parameterization of λ_1 and λ_2 . For details on PAA, see [36] and [37].

$$\hat{\theta}(t+1) = \hat{\theta}(t) + F(t) \phi(t) \varepsilon(t+1) \quad (9)$$

$$\varepsilon(t+1) = \frac{\varepsilon^0(t+1)}{1 + \phi^T(t) F(t) \phi(t)} \quad (10)$$

$$\varepsilon^0(t+1) = w_1(t+1) - \hat{\theta}(t) \phi(t) \quad (11)$$

$$F(t+1) = \frac{1}{\lambda_1(t)} \left[F(t) - \frac{F(t) \phi(t) \phi^T(t) F(t)}{\frac{\lambda_1(t)}{\lambda_2(t)} + \phi^T(t) F(t) \phi(t)} \right] \quad (12)$$

The novelty of the scheme is the use of the non linear controller used in the real WT, since previous approaches of CLOE algorithms supposed LTI controllers. Then, the input to the real plant will be:

$$\beta(t+1) = f(\text{Gain Scheduling}, R/S, N/M, \Omega(t), ru) \quad (13)$$

and the estimated input to the estimated plant model will be:

$$\hat{\beta}(t+1) = f(\text{Gain Scheduling}, R/S, N/M, \hat{\Omega}(t), ru) \quad (14)$$

4. Closed loop identification simulations for Collective Pitch Control Loop

The WT model used is a 2 MW variable speed, variable pitch to feather regulated, with gearbox, 80 meters tower height and 80 meters rotor diameter. The WT model uses 2 modes for modelling the tower fore aft and side to side dynamics. In addition, the WT model uses three modes for modelling the in plane and out of plane dynamics. The WT is modelled in Bladed[®], where the simulated experiments are carried out.

The simulated experiments are developed at rated power and rated speed. In this WT conditions, the collective pitch control regulates the WT. Various turbulent wind speeds are used in order to obtain models for different operating conditions. Operating in closed loop warranties the integrity of the wind turbine, as well as the operation around a specified operating point. The used controller should always be the best available at each time, although this would be far for being an optimum. The procedure can be applied iteratively, [38].

This approach supposes a linear behaviour of the WT only during the experiment. Of course, this can not be warranted before the closed loop identification experiment is carried out. It will mainly depend on the behaviour of the full WT, its controller and of course, the behaviour of the wind. So, experimental data in a real system should be evaluated to warranty that the system has operated close to a fix operating point.

4.1. Simulations design

i. The operational conditions.

It is well known that one of the most complicated problems for system identification in open loop is to maintain the operational conditions during the experiments. For the case of WT identification, where the source of energy is not under control, this problem is even harder. However, operating in closed loop will ensure that the input and output of the plant will remain relatively close to the defined operational conditions, even in the case the controller is not optimum.

Although the wind is not predictable and can suffer big variations during the experiment, the stability of the WT is always warranted since the system is always working in closed loop with a controller which stabilizes the WT. In addition, as long as the wind can be considered as a disturbance at the output of the plant, the wind excursions will not be a problem for plant identification provided that the controller is able to keep the rotor speed at each rated value. However, it is true that if the wind changes a lot during the experiment, the identified model should be used with care, or the experiment should be repeated. For this reason, techniques which require short experiments like the one presented here are more appropriate.

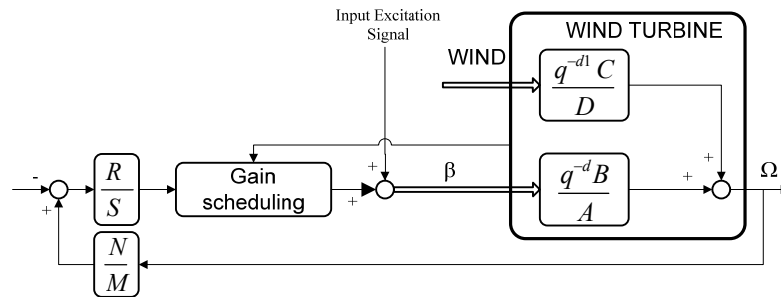


Figure 4. Pitch Control Loop for closed loop identification simulations

ii. Design of the input excitation signal

Several simulations for various wind speeds should be considered. Several input excitation signals may be designed for different wind conditions. In a simulation environment where the wind speed is known a priori, it is easy to select when the input signal should be applied. However, for a real operating WT, where only previous WT states are known, it will probably be necessary to repeat the experiment a number of times.

The input excitation signal can be applied at the demanded generator speed or at the output of the controller. Depending on the selected solution, the input design will be different. For the case of the collective pitch control loop, the input excitation signal has been applied at the output of the controller, as can be seen on figure 4.

The stability and integrity of the WT should not be threatened by the excitation signal, which should be correctly designed, in terms of amplitude and in frequency content.

The design of the input excitation signal is critical for a correct identification of the plant. On one hand the dynamics to be identified should be excited. But, on the other hand, in order to avoid damages in the WT, one should not amplify important undamped modes which do not need to be identified. For a correct design of this input signal, the complete model of the WT is of interest, since it allows testing the feasibility of the experiment. Preliminary trials on simulation tools before developing experiments in a real WT should be considered.

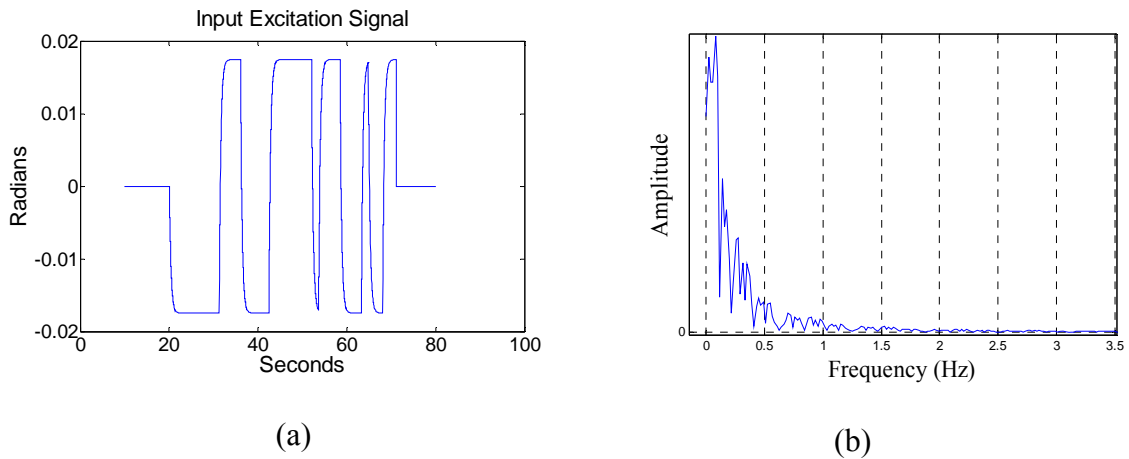


Figure 5: Input excitation signal example. (a) time domain, (b) FFT of input excitation signal

Based on the simulations carried out in Bladed[®] a good input excitation signal for the considered WT can be seen in figure 5. The duration of the experiment is 54 seconds with a total number of 1080 samples for each experiment, sampling frequency: 20 Hz. However, it is probable that a longer experiment would be needed in a real WT because of the presence of a higher level of measurement noise, i.e. a lower signal to noise ratio. The input excitation signal designed is presented in time domain in figure 5.a, and its frequency content is presented in figure 5.b.

It is important to see in figure 5.a that a low energy excitation is used for the identification in closed loop operation. Amplitude of 1 degree, 0.01745 radians, is being used for these simulation experiments of identification in closed loop operation. This amplitude is demanded to the pitch actuators which will rotate the blade at the desired value.

4.2. Simulated experimental data

Several simulations have been done for the identification of WT models from collective pitch demand to generator speed. The selected operational points were characterized by the mean wind speed at hub position during the execution of the simulations, see figure 6 and table 1 for details. The data of the mean wind speed is only used for naming the models which were identified. As can be seen on table 1, the used winds are highly turbulent, in order to be as close as possible to a real operating wind conditions.

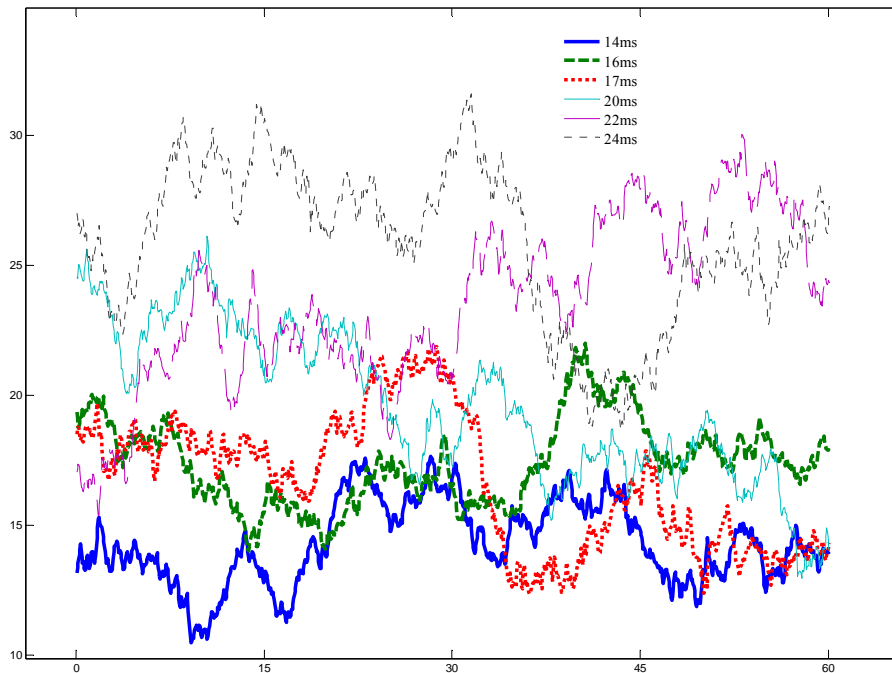


Figure 6 : Wind Conditions at hub during closed loop identification simulations

Case	Std. deviation	Turbulence intensity
14 m/s	1.66 m/s	11.58 %
16 m/s	2.57 m/s	15.29 %
17 m/s	1.68 m/s	9.76 %
20 m/s	2.58 m/s	13.07 %
22 m/s	2.69 m/s	11.29 %
24 m/s	3.15 m/s	12.13 %

Table 1. Wind characteristics at hub during simulations

4.3. Simulated experimental data analysis

Before proceeding to the identification, a preliminary analysis of the acquired data is necessary. It is important to focus on the evolution of the operational conditions of the plant during the experiment. The identification procedure may fail if there are important variations in the operational conditions during the execution of the experiment. Although the active control keeps the rotor speed close to its rated value during the experiment, the nonlinearity of the system can make the identified LTI model unreliable for the pitch controller design.

For data coming from a simulation aeroelastic code, it is easy to see the incident wind. This could not be an easy option for data coming from real WT. However, there are several indirect measurements of the operational point which can be used. One may be the evolution of the controller gain during the experiment. This has been plotted in figure 7 for the duration of developed closed loop identification simulations. The obtained gain variations, for each simulation, have not been a problem for model identification. As was expected a priori, the mean value of the gain, and its deviations, are higher for the cases of lower wind speed. Of course, it should be pointed that time evolution of this gain depends a lot on wind excursions during the experiment.

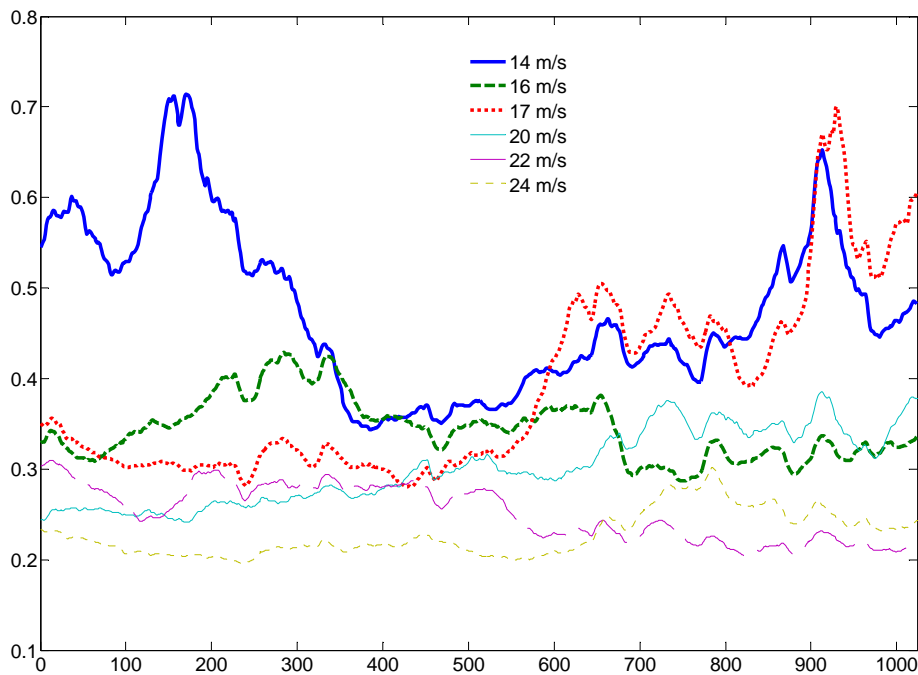


Figure 7: Gain variations during the set of closed loop identification simulations

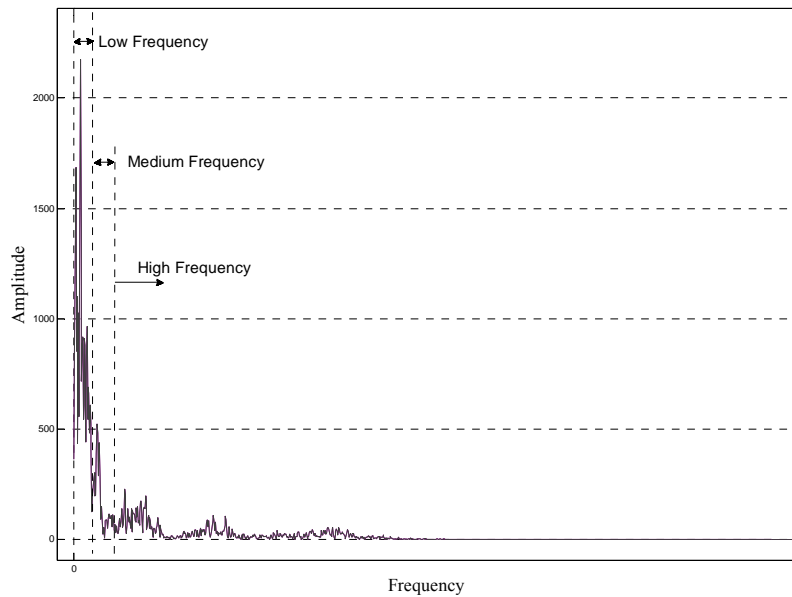


Figure 8: FFT for the measured generator speed for the identification case at 22m/s

It is also important to check the effect that the input excitation signal has on the full WT. A little amount of energy is introduced in the system through this input signal. However, if the signal is not correctly designed, it can produce undesired amplification of different vibration modes. A frequency domain analysis of different variables can give a precise idea of any possible dynamic amplification, in case something unwanted would happen. Such an example is the FFT of the measured generator speed during data acquisition for identification at 22 m/s shown in figure 8. If a frequency correlation between the figure 8 and the WT component modes is done, it can be concluded that no dynamic amplification appears during the experiment for main component's modes. Then, one can conclude that the frequency

content of measured data comes from the plant dynamics and disturbances, without the effect of dynamic amplification of any mode. Similar results can be obtained for all the identified cases.

5. Identified Models

5.1. Algorithm Performance

The performance of the identification algorithms are usually evaluated by so called “model validation techniques” which give clear indication if the identified models can be used for controller design or not. If the model is validated, then it is used for controller design. Unfortunately all the available techniques for validation of models identified in closed loop with CLOE algorithms, makes the assumption that the controller is LTI which is not the case for the pitch loop. Therefore, the evaluation of the quality of the identified models can be done only by evaluating the performances of the control system, using a controller designed on the basis of the identified models.

However, some indications upon the quality of the identified model can be obtained before using the model for controller design. One of these indicators is the covariance matrix of the estimated parameters. It is possible to analyze the evolution of the covariance of each parameter. This will tell if the experiment was long enough and if the frequency content of the excitation signal is rich enough in terms of frequency content. In figure 9 the evolution of the covariance of each element of the identified model is plotted as a function of the number of samples during the identification of the model for the 14m/s case, where n_a is the number of elements of identified denominator and n_b is the number of parameters identified numerator, see eq 5 to eq 8.

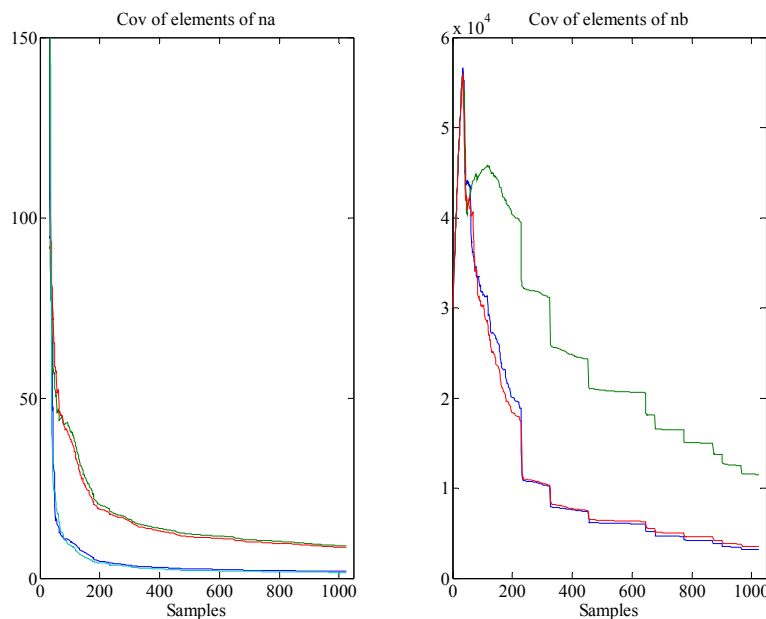


Figure 9: Covariance evolution of the identified parameters for the identification case at 14m/s

In figure 9, it can be observed how the elements of covariance matrix of the identified parameters decrease with the number of samples. This figure also indicates that there is not instability in the algorithm during parameter estimation. It can also be seen that the speed of convergence is faster for the elements of the denominator, as well as its value is much smaller than the ones for the numerator parameters. The convergence of the numerator’s elements is slower, although it seems that both numerator and denominator parameters converge towards a fixed value. In case these values wouldn’t show a clear convergence, the duration of the experiment should be augmented, provided the correct model structure is used.

5.2. Analysis of the identified models

All of the identified models presented here have the same number of poles and zeros. Actually, four poles and two zeros and a delay of two samples has been a good choice for all the analyzed cases. It is important to emphasize that good results have been obtained with the same plant structure for all the identification cases, i.e., the change in the operational conditions influence the value of the parameters but not the complexity of the model.

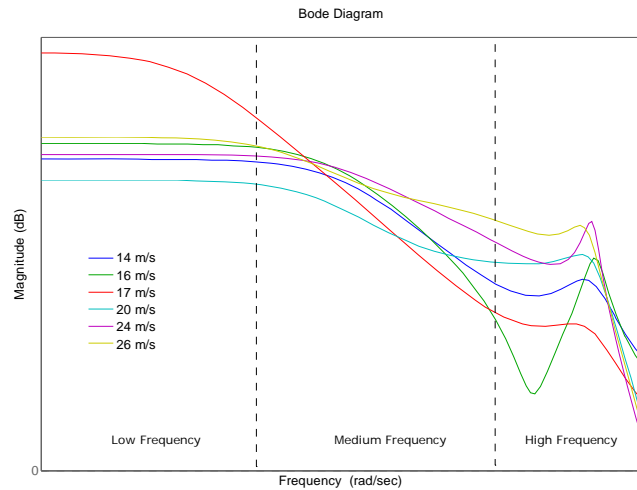


Figure 10: Models obtained supposing LTI controller in closed loop operation

The frequency characteristics are summarized in figure 10. The variations of the dynamic characteristics coming from the different operational conditions can be seen and they are summarized below:

- The models have different DC gain. However, taken into account the length of the experiment, the DC gain of the identified models should be taken with care. It is not possible to identify dynamics at frequencies below twice the inverse of the length of the experiment, in this case 0.035 Hz. It is important to mention that the existence of a pure integrator in the controller would minimize the importance of the knowledge of the exact DC gain value, provided that the identified DC gain is close to the real one.
- At medium frequencies, in general, similar slopes are identified. The behaviour of this frequency region is clearly defined by the dominant dynamic of the rotor inertia.
- Probably, the most relevant differences are at high frequencies, where important difference in the resonance and antiresonance are clearly shown in figure 10. These changes in the frequency characteristics are due to the coupling between the structural dynamics and the collective pitch control loop.

This nonlinear behaviour of the system can also be illustrated by the poles –zeros map of three different linear models obtained at 14m/s, 16m/s and 17 m/s. shown in figure 11. For this particular WT, it can be seen how at certain wind speeds between 16m/s and 17 m/s the systems passes from being non minimum phase to minimum phase⁴. Here one can observe the effect of the wind speed upon its dynamic properties of the system. Not only the parameters of the model changed, but also the system dynamic properties.

It should also be noted that the drive train mode is not identified, as was expected from frequency domain analysis of the measured generator speed shown in figure 8. This is because the frequency analysis of the output does not show any amplification of the drive train mode, and because the damper in the torque loop is active during the execution of the simulations.

⁴ In discrete time models zeros outside the unit circle with positive real part characterize non minimum phase behaviour while zeros inside the unit circle characterize minimum phase behaviour. Zeros outside the unit circle with negative real part may also come from fractional delay in the system, but this is not the case here.

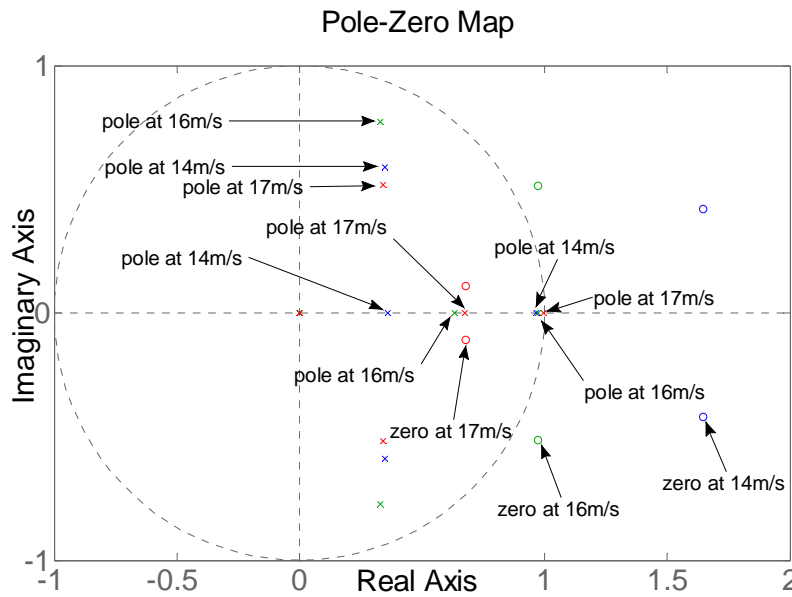


Figure 11: Pole zero map for models which crosses from non-minimum phase to minimum phase plant depending on wind speed velocity

5.3. Validation through Collective pitch controller design and performance evaluation

The existing validation tests for models identified with CLOE cannot be applied since these validation methods suppose linear fix controllers. The model validation can only be done through the following procedure:

- design a controller based on the identified models
- test the controller
- analyze and compare loop performance with different controllers: classical LTI controller with gain scheduling based on linearized models, and the robust linear controller based on identified models.

Therefore, a controller was designed based on linearized models coming from Bladed. A set of linearized models from 12 to 25 m/s wind speed has been used. The design of the PID and of the gain scheduling was done in order to obtain similar control performance for each linearized model.

For the case of the single controller designed on the basis of the identified models a different approach was considered. A robust controller design was developed based on pole placement technique. This controller design gave good performance for all identified model.⁵

The designed LTI robust controller without any nonlinearity, is tested against the aeroelastic code model, and its robustness is proved through a full time domain simulation. The comparison of performances between the two controllers is shown in figure 12.

Figure 12.a shows the wind speed for a simulation of 600 seconds. As it can be observed, the wind speed is moving from 8 m/s to more than 22m/s. In addition, in figure 12.b it can be observed that there is no major difference in the rotor speed error when using the non linear controller and when using the robust LTI controller. Finally, in figure 12.c, the pitch angle demand shows similar activity.

⁵ These technique can not applied to the Bladed linearized models since these models features non observable (or almost non observable modes) and they are numerically ill conditioned

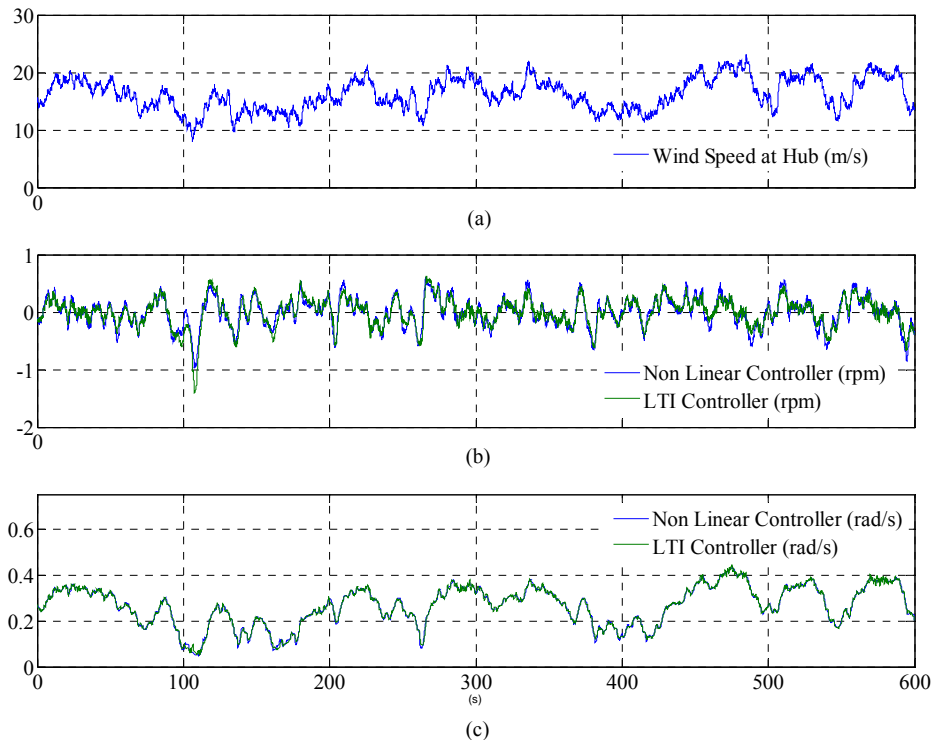


Figure 12: Comparison between non linear controller and a robust linear controller for 600 seconds simulation for high turbulence wind speed. (a) Wind speed. (b) Rotor Speed (normalized). (c) Pitch Angle

6. Conclusions and Future Work

A new algorithm for identifying linear models while a nonlinear controller is running in the feedback loop has been presented. This technique has been applied in order to obtain a set of models from the collective pitch demand to generator speed, at six different mean wind speeds between 14m/s and 26m/s.

The obtained models indicate a correlation between physical knowledge and identified models, in the sense that they show DC gain variations, low frequency dominant dynamic and transition from non-minimum to minimum phase behaviour with operational conditions.

The obtained models are used for a single robust LTI controller design. Its performance is compared to that of a nonlinear controller using a PID controller with gain scheduling. Similar control performances are obtained for both approaches but the linear robust controller is definitely simpler to implement.

The presented procedure and algorithm gives a new tool which makes possible to do model based WT control tuning in site, when controllers designed on theoretical model do not work properly. This procedure avoids dangerous tuning methods based on rules of thumb, and makes possible to check the robustness of the used controllers prior their use since reliable COLM are now available.

Specific real tests for applying this algorithm will soon be developed at NREL's CART2 and CART3 in Boulder, Colorado.

The move towards iterative identification in closed loop and controller re-design, once the LTI controller is implemented, is an interesting option for future studies.

Future developments will deal with the identification of MIMO systems in the frame of individual pitch control. Important uncertainties about flapwise couplings exist, and closed loop identification of the involved loops seems a good tool for analyze this and other effects.

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Appendix. Model Comparison: Identified models vs. Linearized models

There exists the possibility to compare the obtained identified model with the linearized model obtained from Bladed®. This comparison should be done with care, since the origin of the models is totally different. Of course, similar characteristics should be shown, but it should not be expected a perfect match between these models.

Then, it should be kept in mind that there are important differences in the procedure to obtain both models:

- The procedure to obtain linearized models uses constant wind speeds, while identified models use data coming from aeroelastic simulations with three dimensional turbulent wind speeds.
- The procedure to obtain linearized models removes non-linearities in the linearization procedure, especially those coming from the actuators, while the identified model uses the most detailed description of the wind turbine.
- Azimuth dependence and certain other features like tower shadow, upwind turbine wake, yaw motion, gravity loads, safety factors or imbalances are not used for obtaining linearized model, while identified models uses the most realistic representation of the wind turbine dynamics and aerodynamic characteristics.
- The linearized models are obtained in open loop simulation, while identified models are obtained in closed loop operation. This is important since, for example, the drive train mode is always present in the linearized model, but in the identified models, the controller is active and damps this mode which no more appears in the identified models. There are other important differences, like the way the operating point is obtained. In closed loop operation, this is done by the active feedback control, which is not the case for the linearization process of Bladed.

For the case of 16m/s wind, the magnitude Bode plot of the identified model (solid line), and the linearized model (dotted line) are plotted in figure 13. In order to be able to make an easier comparison, the linearized models have been modified to include the drive train damper, active in the identification procedure. It is easy to see that, even the drive train damper has been included in the linearized model, both models looks different in some frequency regions. At this point it is important to remember that the identified model is of order 4, while the linearized is of order 40, which necessary means much more slope changes in this model.

If models are analyzed in ranges of frequency, it is clear that at low frequency there are differences at zero frequency, where linearized models suggest a pure derivator, while a flat gain is obtained in the identified model. In addition, once the slope of the linearized models moves to zero, there is an important gain difference. However, at medium frequencies the models converge to similar values, with the same gain and slope around 1 rad/sec. Clearly, both models represent similarly the big influence of the rotor inertia in the wind turbine dynamic. While frequency moves to higher values, deviations are again evident between both models. But it can be observed that the linearized models shows similar slope changes at the resonance of the identified model, which coincides with a peak in the linearized model. Once again, it is not the comparison of the models which is important, but the performances which can be obtained with the controller designed on the basis of these models (Question: can you say that linearize'd models does not allow to obtain similar performance or that does not allow to design a linear robust controller)

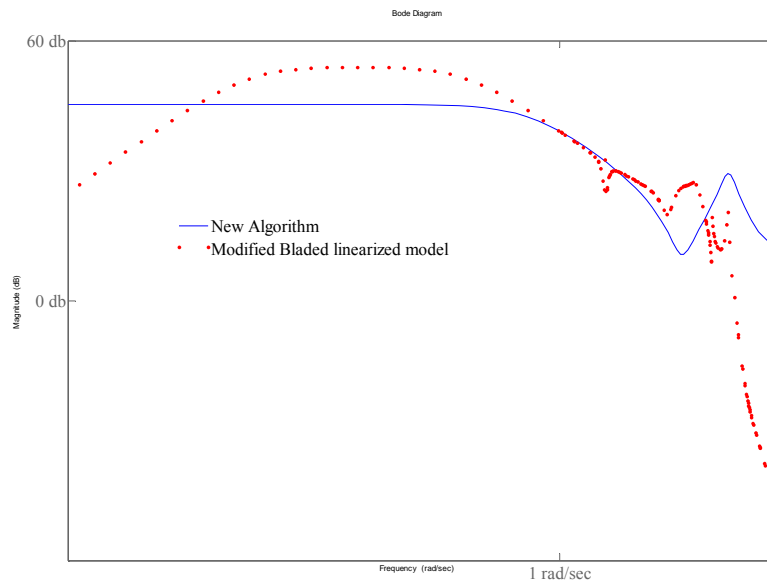


Figure 13: Linear models for 16 m/s wind speed identified with the new algorithm and the linearized model with damper