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"Integrated Wind Turbine Design"

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Contents

1. Introduction to Wind Turbine Identification in Closed loop operation

It is a fact that control loops and its parameters are critical from the point of view of generated loads in a Wind Turbine (WT). It is also true that a wrong mechanical design can not be compensated by a good control algorithm. On the other hand, a good mechanical design can be impaired by a bad control algorithm or parameterization. The tuning of the control algorithms for an individual WT is in many occasions time consuming, inaccurate and does not cope with varying characteristics in time of the hold system. Moreover, it seems to be common in the wind sector 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.

Tuning of control loop parameters for design is a relatively well solved problem in the wind sector, since linear models based on linearization of nonlinear aeroelastic codes are generally used. However, the adequacy of the linearized models can be criticized since in many occasions the control parameters obtained by means of such procedure are not subsequently used in the real WT. In that case, how are these parameters tuned in real WTs? 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.

Therefore there is a need for obtaining relevant and accurate models which can effectively be used for controller tuning.

A very powerful technology for obtaining linear models from data for simple to complicated plants systems, like DC Motor or aircrafts, is the system identification. The open loop identification techniques are well known and have been extensively used. Software tools are also well known. The basics of open loop identification consist on having access to the source of energy which controls the behaviour of the system operating in open loop. Applying an enough exciting signal (in terms of frequency content), the input and the output of the system are collected. After some data treatment (in particular removing the dc components) parametric or non-parametric identification algorithms are used to obtain linear models which should be validated.

However this method has two main drawbacks. Firstly it can be complicated or dangerous to identify in open loop operation when the system to be identified is unstable, has an integrator or an important drift of the operating point occurs, and secondly when the source of energy can not be manipulated by the user. In the case of WT these drawbacks appears since it can be dangerous to operate with the WT in open loop for safety and integrity reasons. On the other hand, the main problem for the implementation of an open loop experiment is that the wind energy, the energy source, cannot be manipulated by the control engineer.

In order to overcome the aforementioned problems, techniques for identification in closed loop operation provide a tool for obtaining realistic linear models based on experiments performed on a real WT or even on non linear aeroelastic simulators. These models can help to a better parameter tuning and can bridge a gap in new control strategies. This technique can also be used for control loop maintenance. The present work describes the idea behind a procedure for obtaining linear models based on “real data” acquired in closed loop operation. Furthermore, first results based on non-linear aeroelastic simulators are presented and discussed by comparison to models obtained by linearization techniques.

There is also another reason for considering the use of these techniques. It was shown and proven experimentally that, if the objective is to identify a model for control design, the models identified in closed loop operation with appropriate algorithms are better in terms of control results than the models identified in open loop.

In order to present this new procedure for obtaining linear models for control purposes, a 1.5 MW Wind Turbine has been chosen. The data for the experiment has been obtained from a non linear model in Bladed®.

For simulation purposes, different wind conditions have been used. The research starts with a low constant wind speed. After that, in order to get a system closer to real operating conditions, new protocols and algorithms were created for three dimensional turbulent wind speeds. At low wind speed, the WT is controlled through the torque demand of the generator. So the torque loop is identified based on this set of wind speeds. For medium to high wind speeds, where pitch loop is active, again three dimensional turbulent wind speeds were used. For this loop, since non linear controllers are very common, new algorithms were created for the identification of the pitch loop

2. Torque Loop Identification

2.1 Constant Wind Speed

2.1.1 Control loop Configuration

Identification in closed loop operation is done in discrete time. Therefore a correct sampling frequency must be chosen for both control and identification purposes. It is commonly extended the idea "the higher sampling frequency, the better controller implementation is obtained". However, this is not always true. The sampling frequency should be chosen not on the available computer speed, but in relation with the dynamics of the system to be controlled and identified. In this case, several frequencies have been used, but 80 Hz is the final frequency chosen. Although this frequency seems too high based on identified dynamics, this frequency has been chosen for convenience in order to present some comparable results.

It is well known that in a variable-speed WT operating at constant generator torque, there is a very little damping for the drive train mode, since torque does not varies with generator speed. The very low damping can lead to large torque oscillations at the gearbox. Although it may be possible to provide some damping mechanically, there is a cost associated to this. Another solution, which is very common in variable-speed WTs, is to modify the generator torque control to provide some damping. More precisely it is used to damp the drive train, the side to side tower and the in-plane rotor modes.

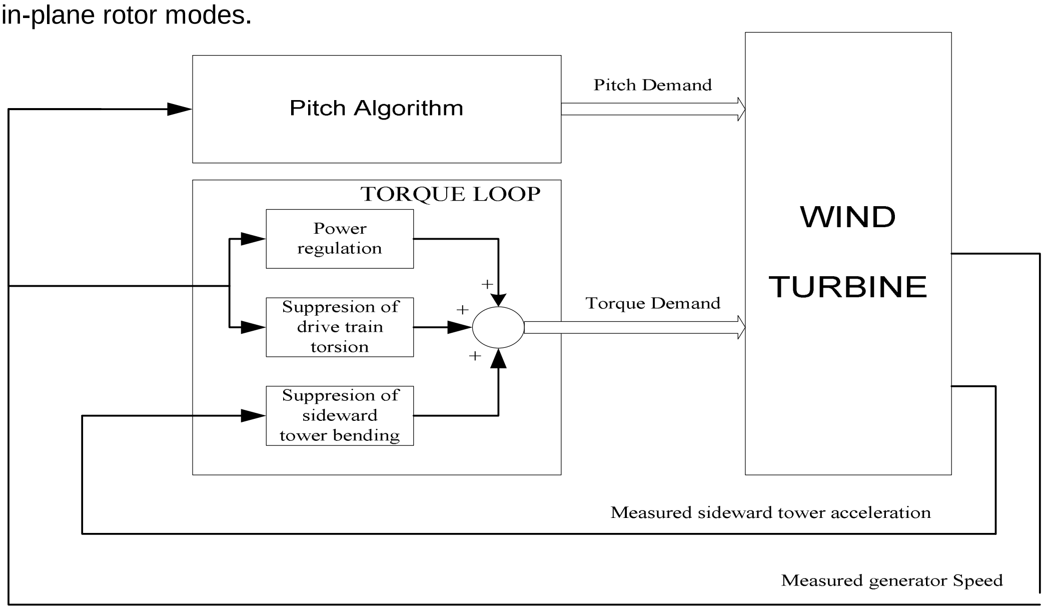


Figure 1. Torque control loop for a wind turbine

In order to be able to perform an experiment for closed loop identification, two options are available for introducing the excitation signal. This can be applied to the reference or to the output of the controller. In this case, the last one has been chosen, so that the final scheme for the closed loop identification experiment is represented in Figure 2.

It can be seen that the selected configuration for the experiment is not the same presented in Figure 1. As long as the experiment is developed in a simulation tool and wind input is constant, the modified loop is not necessary at this stage. On the other hand, if the controller gives a very high damping to the modes mentioned before, it may be not be possible to identify them.

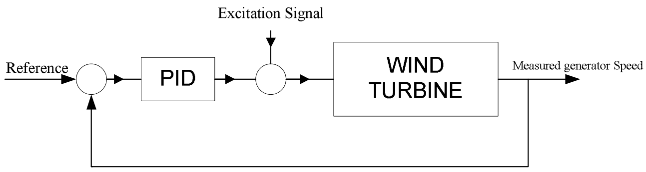


Figure 2. Closed loop scheme used

2.1.2 External Excitation Signal

An important set of different combinations of input signals has been tried. Pseudo random binary signals, step signals, chirp signals, sinusoids, square signals, etc. The frequency shape and amplitude of the input signal has been designed according to the natural frequencies associated to the dynamics of the WT. The design of the input signal is critical, at least, for two different aspects:

- The frequencies that should be identified must be excited. If not, no identification will be possible at those frequencies.
- The stability and integrity of the WT should not be threatened; therefore special care must be taken at lightly damped modes of the tower, drive train, flapwise, edgewise, bending of the blades, etc.

Stability and integrity reasons are critical for the choice of closed loop identification technique, since this technique can be used while stability is guaranteed because the control loop is always active.

For the case of this experiment, a signal, composed of a combination of PRBS, square chirp, and pure sinusoids signals, has been chosen. The input signal is shown in figure 3, and its PSD is shown in figure 4.

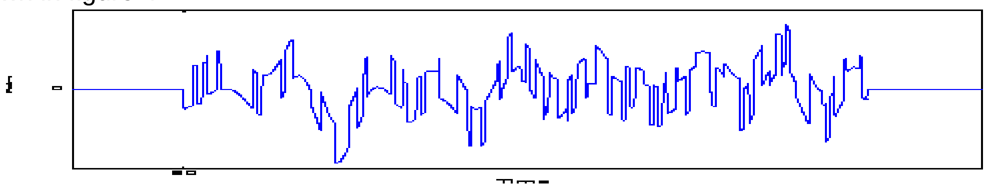


Figure 3: Input signal

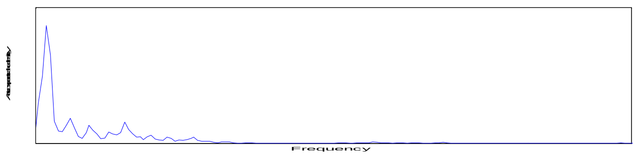


Figure 4. PSD of the input signal

2.1.3 Output of the Experiment

Once the bench mark has been decided, the experimental conditions fixed and the input excitation signal designed, the experiment is performed. In the Bladed® model with constant wind speed, the simulation starts and till 50 seconds no input signal is applied, see figure 3. The reason for doing this is that some time is needed in order to get a steady operation. In this case, a periodic state solution is obtained to which the results of excitation are added. The time domain output data and its PSD are plotted in figure 5 and figure 6.

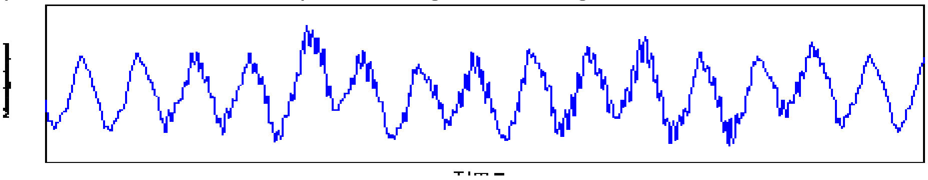


Figure 5: Output signal. Measured Generator Speed

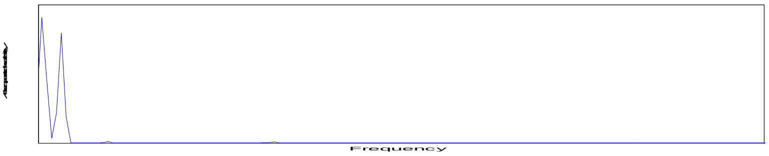


Figure 6: PSD of the Measured Generator Speed signal

2.1.4 Identification Algorithm

Once the set of data from the experiment is available, it is treated (the steady periodic signal is removed) and loaded in Matlab®. Assuming that the real system is linear around an operating point, the objective of system identification in closed loop operation, with our algorithms, is to search for a plant model that in feedback with the controller operating on the true plant, will lead to a closed loop transfer function, (sensitivity function), that is as close as possible to that of the real closed loop system.

Consider figure 7 where the controller is implemented in discrete time (R/S). It is easy to observe that the effective plant input u, is obtained from the external excitation ru through filtering by the output sensitivity function S_{yp} (transfer function from ru to u). The output sensitivity function is given in Equation (1). Its magnitude has a maximum in the frequency regions close to the critical point in the Nyquist plane. Therefore the frequency spectrum of the effective input applied to the plant will be enhanced in these frequency zones. As a consequence, the quality of the identified model in these critical frequency regions for stability and performance will be improved. It has been shown that plant identification operating in closed loop, provided that appropriate identification algorithms are used, leads in general to better models for control design than open loop identification.

$$S_{yp} = \frac{AS}{AS + BR} \quad (1)$$

Unfortunately, in the meantime, the feedback introduces a correlation between the measurement noise and the plant input. This leads to an important bias on the estimated parameters if one would like to identify the plant model with open loop identification techniques based on no correlation. One may expect that the open loop techniques based on the whitening of the prediction error will still provide good results in closed loop operation. However, as a consequence of feedback, interdependence between the noise model and the plant model occurs and the parameter estimates will also be biased.

Therefore, for a correct identification in closed loop one needs identification methods that take advantage of the improved characteristics of the effective excitation signal applied to the plant input but are not affected by the noise correlation introduced by the feedback. There are a few available algorithms for closed loop identifications.

These are parametric algorithms, so an iterative work is needed in order to deal with a good combination for the degrees of the polynomials and delay. All of these methods have been tried.

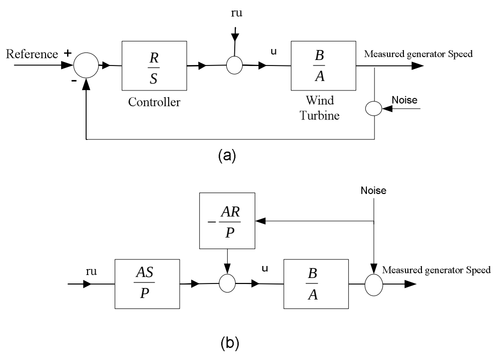


Figure 7: a) Identification scheme in closed loop. b) Equivalent scheme

The objective of the model validation in closed loop is to find what plant model combined with the current controller provides the best prediction of the behaviour of the closed loop system. These identified models should always be validated. Some validation tests applied are:

- Whiteness test. The statistical whiteness test of the residues (difference of the real output of the plant and the system in closed loop identified as in an open loop plant).
- Independence test. The statistical independence test between the residues (difference of the real output of the plant and the estimated output of the identified plant in closed loop with the controller) and the real output of the plant. This test assures the estimation of unbiased parameters, as well as the absence of correlation between the closed loop output error and the external excitation.
- Closeness of closed loop poles, where the poles of the closed loop system identified as an open loop plant, and the computed poles for the identified plant in closed loop with the controller are compared.
- Vinnicombe gap. This is a rigorous method to compute the difference between the real sensitivity transfer function (identified as an open loop system), and the sensitivity transfer function computed with the identified plant and the actual controller running.
- Frequency validation. It consists of a Bode plot of the estimated plant in closed loop with the controller, and the Bode plot of the closed loop system identified as an open loop plant.
- Time domain validation in closed loop, where the real output and the estimated output of the identified plant in closed loop with the controller, are plotted. This test, as well as the frequency test will give an indication of the quality of the identified model.

2.1.5 Results

The results of validation test are depicted in Figure 8, for one of the best identified models. From Figure 8.a it can be seen that the frequency domain validation is quite good until 0.2 f/fs, where a ripple in the model appears because the sampling frequency seems to be too high compared with the identified dynamics. This leads to the need of high order models to pass the validations tests. It is important to see that the quality of the frequency band needed in the model for control design is well identified however. The Figure 8.b shows the whiteness test. It is not passed mainly because of the first samples, however it is bad enough to discard the model of the closed loop used in the validation procedure. However in Figure 8.c, it can also be seen that the independence test is passed, as well as the closeness of the poles in Figure 8.d. Finally, the time domain test seems good with a loss function of 0.00028167 while the Vinnicombe gap value is 0.0016816. Figure 8.f gives the bode diagram of the identified model, where the drive train and the in-plane modes can be seen. It also shows the high activity at the highest frequencies, as previously commented upon, which can be treated.

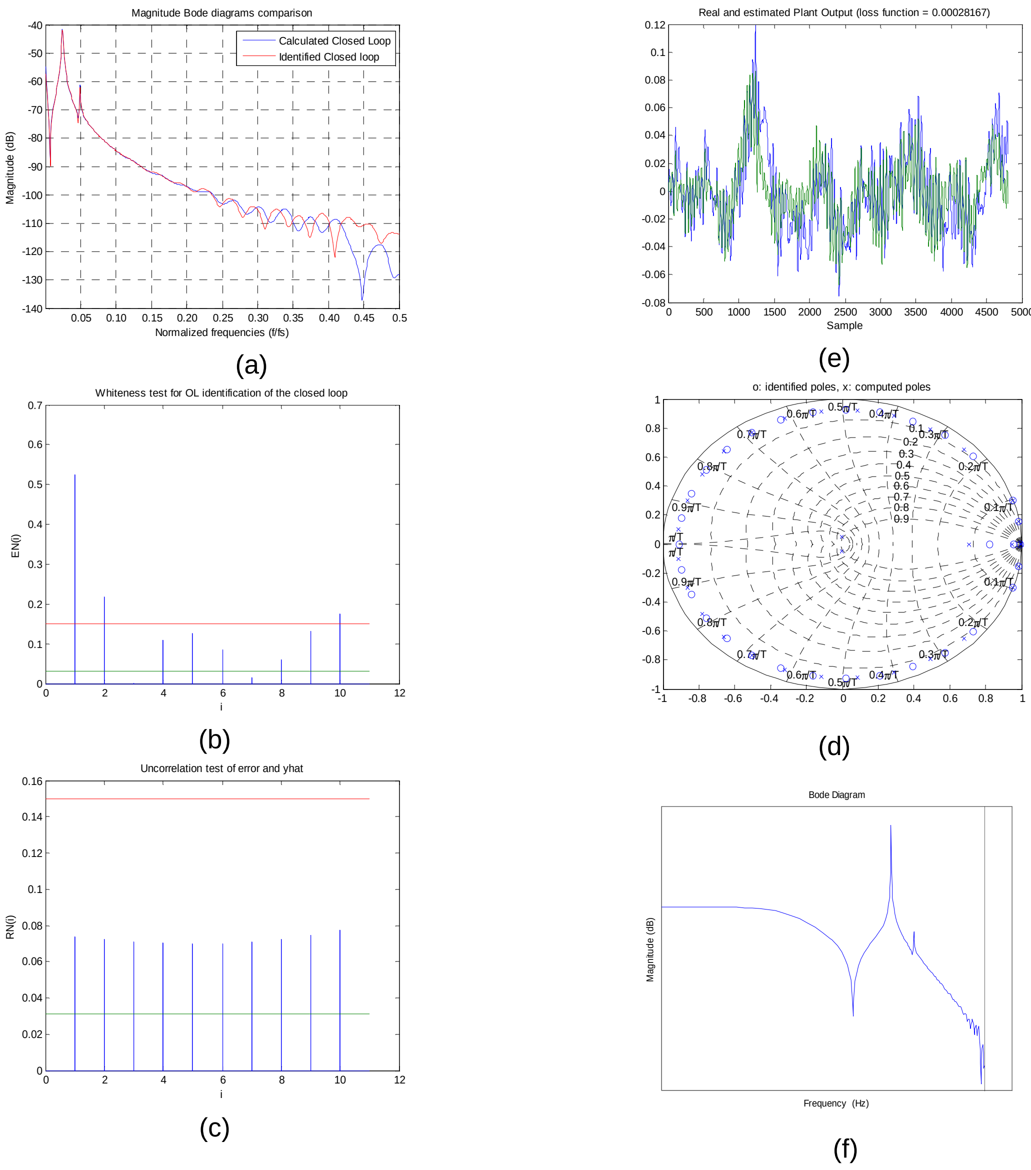


Figure 8: Closed loop Validation tests. Vinnicombe Gap = 0.0016816. a) Frequency domain validation. b) Whiteness Test. c) Independence Test. d) Closed loop poles closeness. e) Time domain validation. f) Bode diagram of identified plant.

2.2 3D Turbulent Wind Speed

In order to identify linear models for control purposes, a set of data acquired on a plant is needed. For this work, a three-bladed variable speed pitch controlled WT has been chosen, in order to have a WT behaviour closer to a typical real turbine. The data for the experiment has been obtained from its non linear model in Bladed®[7]. For the identification of the transfer function from the generator torque demand to measured generator speed, a standard fatigue case is used.

Figure 9, shows the nominal wind speed measured at the hub position. An important variance can be seen. The turbulence intensity for lateral, vertical and longitudinal wind is between 20% and 35 %. For the case of this set of data, the longitudinal mean speed of the wind is 2.7 m/s. At such low wind speed, the WT is controlled through the torque demand of the generator. Some times, small changes in pitch angle are implemented in order to improve power production at low wind speeds. However, in order to avoid problems concerning MIMO control-identification problems, the pitch is held constant during the identification procedure.

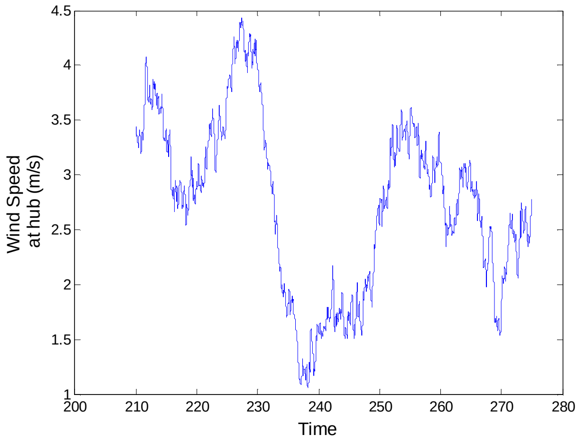


Figure 9. Three dimensional turbulent wind. Nominal wind measured at hub position.

2.2.1 Input Excitation Signal

Once again, the design of the excitation signal for system identification is crucial. On one hand the dynamics to be identified should be excited and on the other hand, care should be taken because there can be important lightly-damped modes which need to be identified, but should not be amplified in order to avoid damage to the WT. For a correct design of this input signal, the detailed model of the design process of the WT can be of certain interest. Stability and integrity reasons are critical for the choice of closed loop identification technique, since this technique can be used while stability is guaranteed because the control loop is always active. The stability and integrity of the WT should not be threatened; therefore especially care must be taken at lightly damped modes of the tower, drive train, flapwise, edgewise, bending of the blades, etc. So, for this case, the a-priori information about the drive train torsion frequency or the side to side and in-plane frequencies should be taken into account. The frequency shape and amplitude of the input signal should be designed according to the natural frequencies associated to the dynamics of the WT.

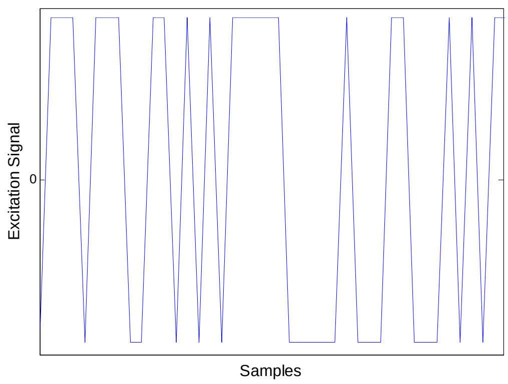


Figure 10: Small set of the Input signal

An important set of different combinations of input signals has been tried. Pseudo random binary signals, step signals, chirp signals, sinusoids, square signals, etc. Finally a PRBS has been selected. The PRBS is generated by means of shift registers with feedback (implemented in software). The number of cells in the shift register used was N = 11, which generates a PRBS with a length of 2047 samples ($2^N - 1$). With this PRBS configuration, the lowest frequency that can be identified using one PRBS sequence is 3.63 Hz, [6]. Then, in order to try to get a better identification at lower frequencies, the sequence of 2048 samples has been repeated once, in order to enlarge the frequency content at low frequencies, moving to almost 60 seconds of experiment length. So a better identification at the interesting frequency range should be obtained. It is important to emphasize that the amplitude of this input signal does not need to be significant. For this case, the input signal is around 10% of the mean value of the generator demand during the experiment. This 10% corresponds with the 0.25% of the nominal torque of the generator. This means, that the amount of energy which is needed for doing identification in closed loop operation is very small and that the stress on the system is negligible. In figure 10 the input excitation signal has been plotted for a period of one second.

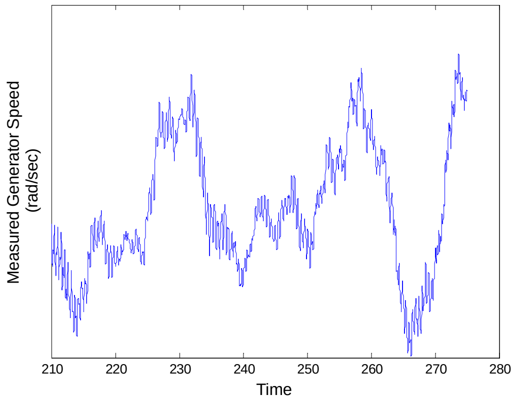


Figure 11: Output signal. Measured Generator Speed

2.2.2 Output of the experiment

Once the benchmark has been completely defined, the experimental conditions fixed and the input excitation signal designed, the experiment is performed in Bladed® for a three dimensional turbulence wind speed fatigue case. At this point, the only decision that should be taken is when should be run the experiment. Since this procedure is designed for identification of torque loop, and no interaction with pitch control is desired, the experiment should be done in the presence of low wind speed, which in addition is interesting from the point of view of WT integrity. For a real WT case, information from the anemometer and power production would be needed. For a simulation environment this is not critical, since the wind speed as well as the behaviour of the system is known a priori.

The time domain output of the experiment is plotted in figure 11. It can easily be observed that there is an important ripple of high frequency which corresponds to the different lightly damped modes of the drive train and tower side to side modes. It is also possible to realize that an important low frequency content appears in the output because of the different excitation signals of 3P and 6P, as well as because of the effect of the three dimensional turbulence of the wind. It is easy to realize that there is a big correlation between the measured generator speed and the nominal wind speed measured at hub position, see figure 2. All off this frequency content can be seen in the FFT plot of the output on Figure 12.

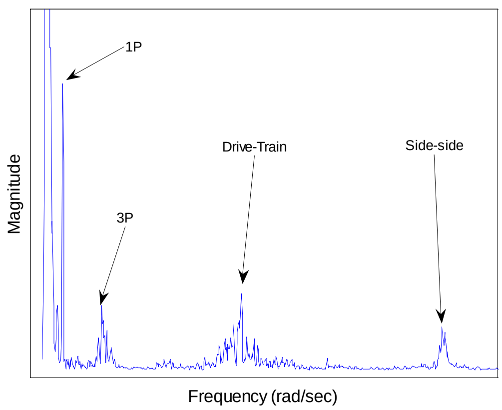


Figure 12: FFT of the Measured Generator Speed signal

2.2.3 Closed loop identification algorithm

The objective of our algorithm for system identification in closed loop operation is to, once again, search for a plant model that in feedback with the controller operating on the true plant, will lead to a closed loop transfer function, (sensitivity function), which is as close as possible to that of the real closed loop system. Of course, this is possible assuming that the real system is linear around an operating point for small signal variations. On has to note that the system is able to stay around this operating point, because of the effect of the acting controller.

Of great importance is the selection of the model structure to be identified. At this step, the noise model is the main decision to be made, when choosing the algorithm to be used. For constant wind speed, an ARMAX structure was selected, eq (2). In order to be able to identify an ARMAX model in closed loop operation, the XCLOE method was used,

$$A(q^{-1})\ y(t) = q^{-d} B(q^{-1})\ u(t) + C(q^{-1})\ e(t) \tag{2}$$

The structure of the noise model depends on the disturbance that appears on the system. In the framework of WT, there are disturbances of 1P, 3P, 6P,…[4]. Also there are several frequencies involved and they are usually very narrow band disturbances. This set of disturbance is much stronger in the measured generator speed for the case of three dimensional turbulence wind speed, see figure 12.

2.2.4 Validation Tests

Once a model identification is done, validation tests should be performed in order that the model be qualified for control design. The validation tests are always needed for an identified model, obtained in open loop or in closed loop. The validation tests depend on the identification technique which is used, and on the algorithm selected. The validation tests in closed loop help to decide which model is correct and which one is not correct. In addition, the validation tests help to decide among several validated models which one is the best. At the end of the identification process, there will be one model which will be better in terms of the validation test applied to the set of identified models. For the case of identification in closed loop operation, the objective of the model validation in closed loop is to find what plant model combined with the current controller provides the best prediction of the behaviour of the true closed loop system.

These tests will usually give an indication of the quality of the identified model.

2.2.5 Model Identification Results

From figure 13.a it can be seen the frequency domain validation, (linear frequency scale and log normalized magnitude scale). Both sensitivity functions, the identified and the computed, are quite close until 0.15 normalized frequency (i.e. 12 Hz), where a ripple begins. Also, a small difference seems to appear at low frequencies, where there is a bit of difference between the identified sensitivity function and the computed one. This may come from the low energy of the input excitation signal at very low frequencies. The differences at high frequencies are less important since they are out of the control bandwidth. In figure 13.b, the closeness poles test is depicted. Here it can be seen that poles of the identified sensitivity transfer function, and the computed sensitivity transfer function, are very close, especially within the bandwidth of the control loop. This means that the estimated plant model is correct since the two systems use the same controller. On the other hand, the Vinnicombe distance between the identified and the computed sensitivity transfer function is 0.0474, which is a very low value. The statistical test has been also done. To do this, normalized cross correlations have been computed as indicated earlier. This test has been passed by the model, since all values of the normalized cross correlations are below the threshold level of 0.15. Then, it can be concluded that the estimated parameters of the model identified with CLOE algorithms are correct and that the model can be used safely for controller design. The time domain validation test is omitted since, although it can be plotted, the plot does not take into account the noise model, which in addition has different

different converge properties, and its view does not give additional information to the validation process.

2.2.6 Comparing Linearized Models with Identified models

At this point one has three models for the plant: 1) the model identified in closed operation in the presence of three dimensional turbulence wind speed, 2) the model identified at constant wind speed, and 3) the linearized model obtained from Bladed® at 3 m/s. These control models have been obtained by different methods but from the same model and simulation tool. Therefore one can consider a comparative validation.

The linearized model is not a good model for control design since even if the controller used during closed loop identification stabilizes the true plant (the nonlinear Bladed model) does not stabilize the linearized model of the plant (there are certainly numerically problems inherent to the method used to generate this model).

The results for the validation of the model identified with constant wind speed are shown in figures 14a and 14b. The results are close to those obtained for the model identified in the presence of wind turbulence. A slightly higher difference can be noticed at low frequencies between the computed closed loop transfer function and the identified closed loop transfer function, but the computed and identified closed loop poles look to be as close as for the case of the model identified in the presence of wind turbulence. The Vinnicombe distance is 0.0412 which is also very close to the value obtained for the model identified in the presence of wind turbulence (differences below 0.01 are absolutely not significant).

Therefore despite that the model identified in this paper has been obtained in the presence of wind turbulence, it is as good as the model identified at constant wind speed.

The magnitude versus frequency characteristics of the three models have been plotted in figure 15. The model identified in closed operation in the presence of three dimensional turbulence wind speed (solid line), the model identified at constant wind speed (dash line), and the linearized model obtained from Bladed at 3 m/s (dash dot line).

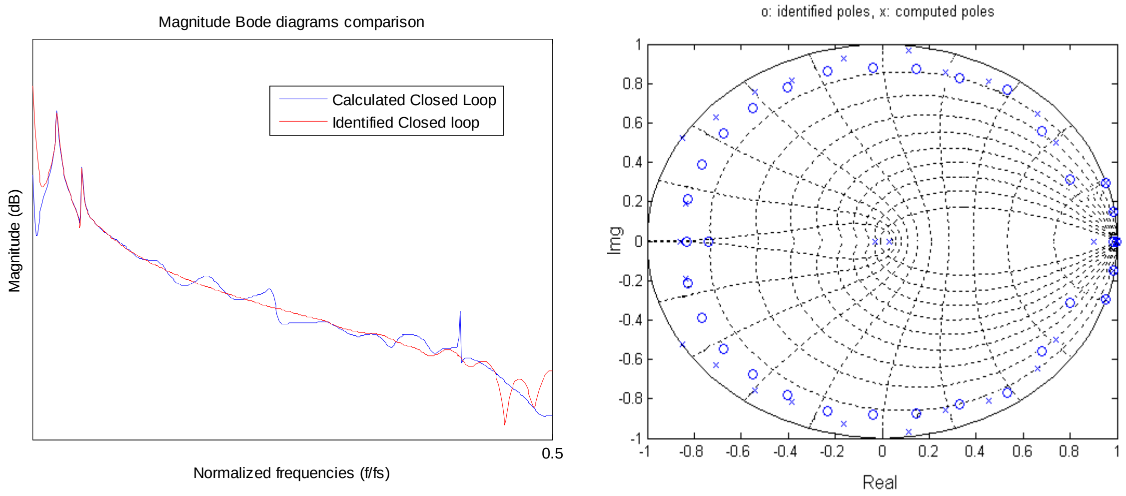
The differences between the models can be summarized as follows:

- A positive slope is observed at lowest frequencies in the linearized model, while a constant gain is obtained for the identified models.

- The resonances (complex poles) and antiresonance (complex zeros) are almost at the same frequencies for the model from [13] and the linearized model, but the dampings are different

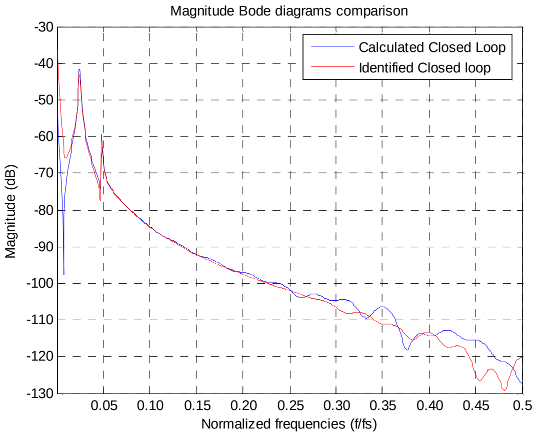
- The model identified in the presence of wind turbulence shows the same resonances and antiresonance as model identified with constant wind speed, except in the medium frequency range where the effect of a close resonance and antiresonance is smoothed (which is good for control design purposes).

The final conclusion which can be drawn from the comparative model validation in closed loop, is that the model identified in closed loop in the presence of wind turbulence is as good as the one identified at constant wind speed (which is not a very realistic situation) and both are better that the model obtained by linearization. It is important to mention however that this conclusion is valid for models to be used for control design which capture only the features necessary for this task (they do not replace a physical model).

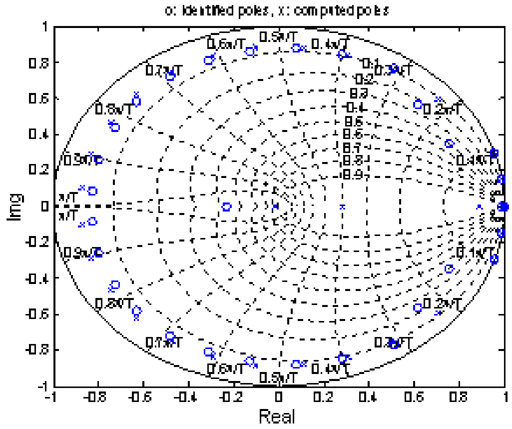


(a) (b)

Figure 13: Closed loop Validation tests for identified model for the case of three dimensional turbulence. Vinnicombe Gap = 0.0474. a) Frequency domain validation. b) Closed loop poles closeness.



(a)



(b)

Figure 14: Closed loop validation tests for the model identified at constant wind speed. Vinnicombe Gap = 0.0412. a) Frequency domain validation. b) Closed loop poles closeness.

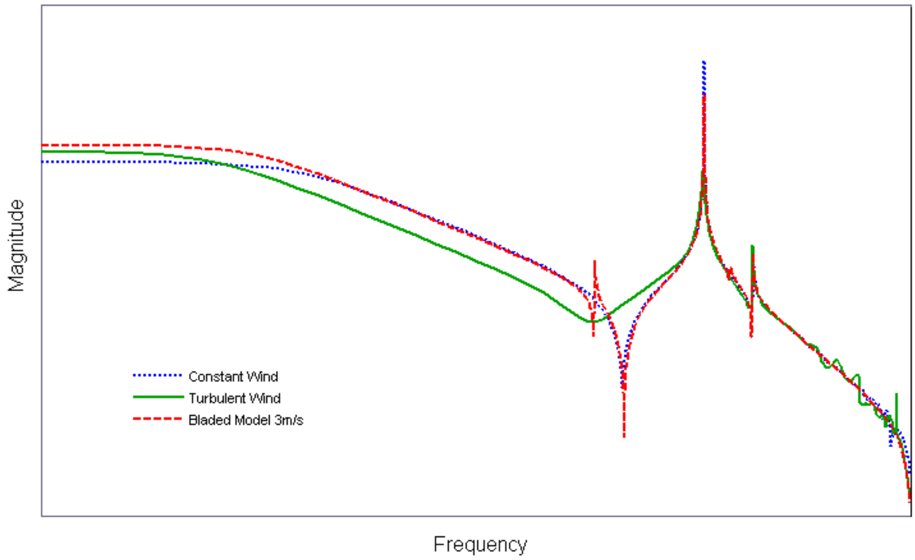


Figure 15: Linear models. Solid, model identified in presence of disturbance. Dash, model identified at constant wind speed. Dash-dot, linear model obtained from Bladed at 3 m/s.

3. Pitch Loop Identification

This chapter deals with the extraction of LTI models for the pitch control loop to be used in control design. A new closed loop identification algorithm which can be applied in the presence of time varying controllers has been developed and applied in the frame of the pitch loop of WT.

3.1 Pitch Plant Overview

Pitch loop dynamics are complex and have been extensively studied. Many important details should be taken into account for modelling the Pitch dynamics, from the aerodynamics to tower and blade dynamics, drive train... Many efforts in describing the physics have been done in this field, and here only some remarks concerning the control problem will be briefly commented.

There exists a very well known nonlinear relationship between the extracted power from the wind, P, and the wind speed, V. Such relation is given in eq.3, where ρ is the air density. The extracted power is linear with the area of the rotor characterized by the blade's radius, R. The term Cp in eq.3 deals with the characterization of the aerodynamic performance of the rotor blades. λ is the well known tip speed ratio, which characterizes the relation between the incident wind speed, and the speed of blade's tip. Then, the power which can be extracted from the wind, depends on the wind speed (V), blade's radius (R) and pitch angle, (β), and rotor speed(Ω) Taking into account that common rated wind speeds are between 10m/s and 14 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.

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

The aerodynamic torque is also highly non linear with the wind speed. It is known that the aerodynamic torque can be treated as two separate components, one depending on blade pitch and rotor speed, and a second part depending only on wind speed, as is shown in eq.2. Then, the wind can be treated as an output disturbance occurring in a control problem. Only $h(\beta,\Omega)$ is present in the direct loop, and nonlinear effects would only come through the pitch angle and the rotor speed, but not on the wind speed. Even more, taken into account that rotor speed deviations from rated speed are commonly small, the dependency of the torque with the rotor speed may be ignored.

$$T(\beta,\Omega,V) = h(\beta,\Omega) - g(V) \tag{4}$$

All of these features of the pitch loop, as others like aerodynamic effects, like dynamic inflow, dynamic stall, tower shadow or imbalanced rotor can 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, that this effect on the output is sometimes more powerful than the effect of the pitch demand or generator torque demand. The effect of these disturbances when using a simple PI controller can cause unwanted activity of the pitch actuator at these frequencies. This activity can cause an amplification of these disturbances, which can get the WT to collapse if they are not taken into account in the controller design.

3.2 Classical Pitch Control Loop

For variable speed WT configuration, the pitch control loop is active at medium and high wind speeds. The main objective of the pitch loop is to modify the pitch angle of the blade in order to control the power production as well as the rotor speed while trying to reduce mechanical loads. The most popular WT 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 aerodynamic forces coefficients. If the pitch angle increases in this range, the angle of attack decreases. If the wind speed increase, 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 conditions at higher angles of attack, where higher uncertainties appear and the linear relationship disappears. All these effects should be taken into account when designing the pitch control loop.

In order to regulate the generator speed, any general polynomial controller, *R/S*, can be used. According to the main pitch dynamic, particular low order controllers like PI or PID are commonly used. This is theoretically correct because of the low order of the dominant dynamic of the pitch plant, coming from the huge inertia of the rotor. In addition, the use of PI controllers, (and sometimes PID), is very common since they are relatively easy to tune based on rules of thumb when the predesigned controller doesn't work as was expected from simulations.

However, a simple PID cannot deal with the non-linear aerodynamic effects coming from eq.1. There is certainly an important change in the gain of the pitch plant coming from the wind speed variations. So, the controller should accommodate the pitch demands to the wind excursions and variations. Then, a common solution is to implement a gain scheduling based on indirect measurements of wind speed. The gain scheduling introduces a non-linear and time varying behaviour to the controller since its will depend upon the wind speed. The introduction of this non-linear controller in the pitch feedback loop makes useless the known identification algorithms for identification in closed loop operation which all require the use of a LTI controller.

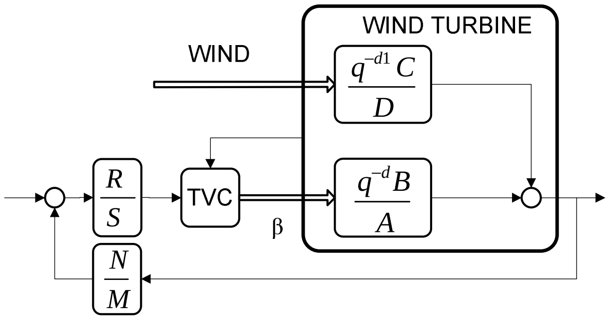


Figure 16. Classical Pitch Control Loop representation

Note that the undamped torsion mode of the drive train is always present in the pitch dynamics; however this is usually damped in the torque loop. So if this torsion mode is correctly damped, it is commonly invisible in the pitch control loop. Then, no resonance is expected to appear at the drive train frequency. However, it is usually needed to introduce some filters in order to remove or to attenuate the frequency content at those frequencies which can affect the stability of the WT like the nP frequencies or the tower mode.

All of these classical solutions for the pitch loop regulation are summarized in Figure 16, where:

- *d* represents the integer delay between the pitch actuation and the generator speed (in terms of sampling periods)
- *B* and *A* represents the numerator and denominator of the pitch plant model
- *TVC* represents the time varying controller
- *R* and *S* represents the numerator and denominator of the linear controller, normally a PI or PID
- *N* and *M* represents the numerator and denominator of the filters in the feedback loop
- *d1*, *C* and *D* represents the disturbance model of the pitch loop, governed mainly by the wind

The pitch control loop presented is a classical control scheme commonly used for the regulation of the power and generator speed. Although this control scheme can be more complicated, this one is representative enough of the actual state of the art.

3.3 The new Algorithm for Pitch Plant Identification, operating in closed loop with non linear Controller

The purpose of this research is the identification of the pitch to generator speed transfer function based on experimental data, while operating in closed loop. The algorithm developed for the identification of the pitch plant, shown in figure 17, is an extension of CLOE family algorithms for the case of nonlinear time varying controllers. 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.

Suppose the real, Ω, and estimated, $\hat{\Omega}$ generator speeds are given by, eq. 5 and eq. 6, where β is the pitch angle, e is white noise and ε the predicted error:

$$\Omega(t) = \frac{z^{-d}B(q^{-1})}{A(q^{-1})}\beta(t) + \frac{z^{-d1}C(q^{-1})}{D(q^{-1})}e(t+1) \tag{5}$$

$$\hat{\Omega}(t) = \frac{z^{-d}\hat{B}(q^{-1})}{\hat{A}(q^{-1})}\hat{\beta}(t) + \frac{z^{-d1}\hat{C}(q^{-1})}{\hat{D}(q^{-1})}\varepsilon(t) \tag{6}$$

where:

$$A(q^{-1}) = 1 + a_1 q^{-1} + \ldots + a_{nA} q^{-nA} \tag{7}$$

$$B(q^{-1}) = b_1 q^{-1} + \ldots + b_{nB} q^{-nB} \tag{8}$$

$$\hat{A}(q^{-1}) = 1 + \hat{a}_1 q^{-1} + \ldots + \hat{a}_{nA} q^{-nA} \tag{9}$$

$$\hat{B}(q^{-1}) = \hat{b}_1 q^{-1} + \ldots + \hat{b}_{nB} q^{-nB} \tag{10}$$

characterize the real and estimated models of the pitch dynamics. The real measured output of the system, eq.5, and the estimated plant output, eq.6, are used to compute the closed loop error, (ε $= \Omega - \hat{\Omega}$). This quantity is used by the Parameter Adaptation Algorithm (PAA), which recursively estimates the parameters of the plant. The input excitation signal, r_u, is applied in this case at the output of the controller, see figure 17.

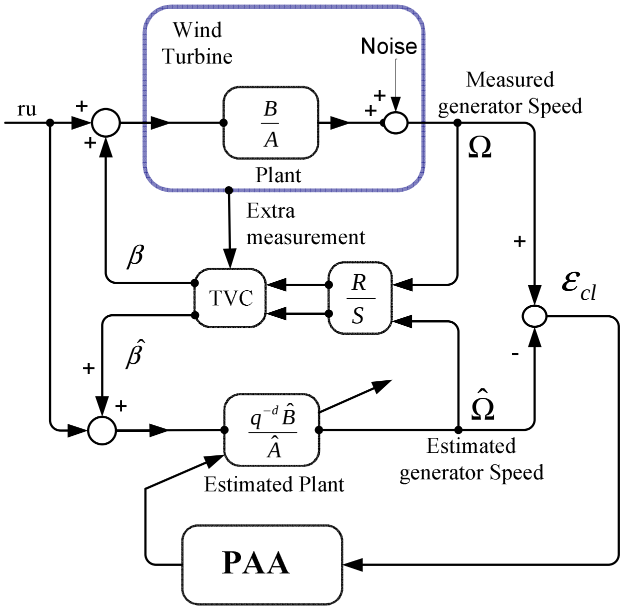


Figure 17. The new closed loop identification algorithm scheme used for pitch loop model identification

The estimated parameters can be arranged in a vector of parameters θ, to be estimated. The measurements loop can also be arranged in a measurements vector, Φ, and used in the PAA. The PAA algorithm is defined by equations 11 to 14.

$$\hat{\theta}(t+1) = \hat{\theta}(t) + F(t)\,\phi(t)\,\varepsilon(t+1) \tag{11}$$

$$\varepsilon(t+1) = \frac{\varepsilon^0(t+1)}{1 + \phi^T(t)\,F(t)\,\phi(t)} \tag{12}$$

$$\varepsilon^0(t+1) = w_1(t+1) - \hat{\theta}(t)\,\phi(t) \tag{13}$$

$$F(t+1) = \frac{1}{\lambda_1(t)}\left[F(t) - \frac{F(t)\,\phi(t)\,\phi^T(t)\,F(t)}{\frac{\lambda_1(t)}{\lambda_2(t)} + \phi^T(t)\,F(t)\,\phi(t)}\right] \tag{14}$$

The novelty of the scheme is the use of the real time varying non linear controller used in the real WT, since previous approaches of CLOE algorithm supposed LTI controllers. Then, the pitch demand will be:

$$\beta(t+1) = f(TVC, R/S, N/M, \Omega(t)) \tag{15}$$

and the estimated pitch demand will be:

$$\hat{\beta}(t+1) = f(TVC, R/S, N/M, \hat{\Omega}(t)) \tag{16}$$

3.4 Identification Experiments on Aeroelastic Code Bladed

3.4.1 Experiments Design

Several experiments have been developed for a multi-megawatts WT. These simulations have been done in Bladed®. The procedure for designing the experiments is presented next.

i. Design of the input excitation signal

The design of the input excitation signal is critical for a correct identification of the plant, so it should be considered with care. Preliminary trials on simulation tools before trying it in a real WT should be considered. Based on the experiments carried out in Bladed®, a good input excitation signal for the analyzed WT can be seen in figure 19. The duration of the experiment is 54 seconds with a total number of 1080 samples for each experiment. 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).

It is important to see in figure 19.a that a low energy excitation is needed for the identification in closed loop operation, but which is important is and appropriate frequency content. Too small amount of energy at certain critical frequencies, would probably not allow the correct identification of the pitch dynamics.

ii. 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.

It is important to realize that 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, at least, stabilizes the WT. In addition, as long as the wind can be considered as a disturbance at the output of the plant according to eq.4, the wind excursions will not be a problem for plant identification. However, it is assumed that during the experiments the pitch angle variations are not too large in order to preserve the linearity of the plant model.

Of course, several experiments for different wind speeds should be considered, and probably different input excitation signals should 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.

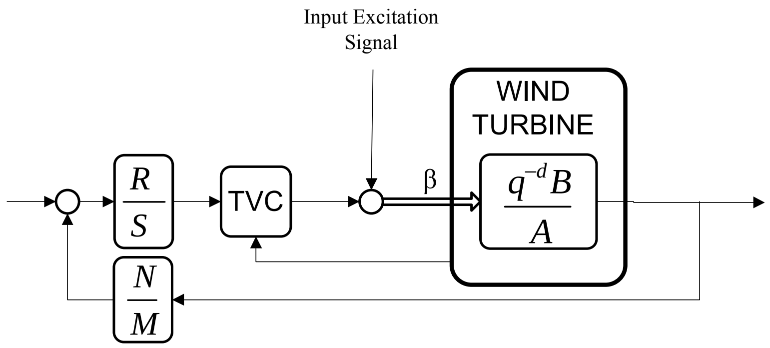
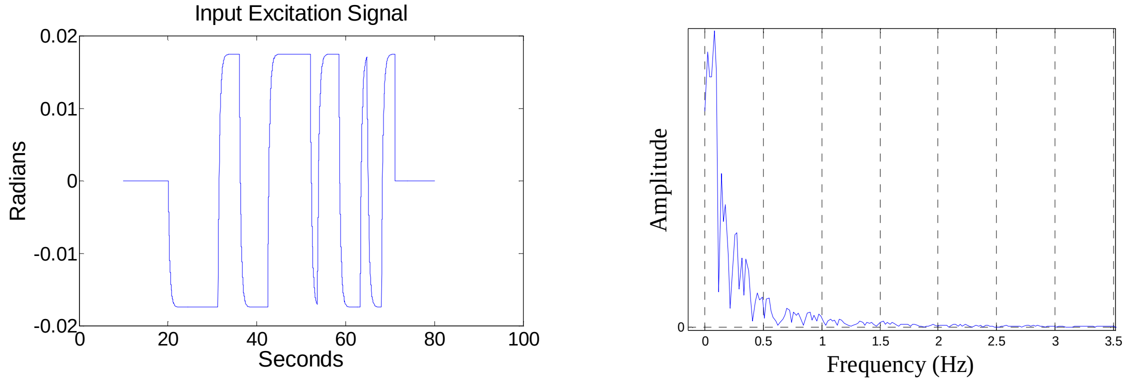


Figure 18. Pitch Control Loop for closed loop identification experiments

The input excitation signal can be applied at the reference of the control loop or at the output of the controller. Depending on the selected solution, the input design will be different. For the case of the pitch loop, the input excitation signal has been applied at the output of the controller, as can be seen on figure 18.

3.4.2 Experimental data

Several experiments have been done for the identification of the pitch loop for the multi-megawatt WT model. The selected operational points were characterized by the mean wind speed at hub position during the execution of the experiment, see table 1 for details. The data of the mean wind speed is only used for naming the models and for taken this information into account for the control design in a latter step.



(a) (b)

Figure 19: Input excitation signal example. (a) time domain, (b) FFT of input excitation signal.

Taken into account the comments on previous sections, several input excitation signal were tested, although for this particular wind turbine the same signal has been used for the whole set of experiments. For a different WT another input signal may be necessary to be considered. The input excitation signal designed is presented in time domain in figure 19.a, and its frequency content is presented in figure 19.b.

As can be observed in figure 19.a, the experiment takes only 54 seconds. The wind conditions for these 54 seconds at hub position for all the set of experiments developed can be observed in figure 5. It can be observed that the wind is highly turbulent. Table 1 shows the standard deviation and the intensity of the turbulence at the hub position.

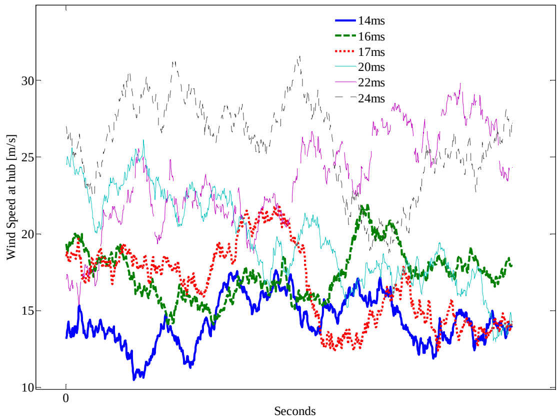


Figure 20: Wind Conditions at hub during closed loop identification experiments

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 experiments

Before proceeding to the identification, a preliminary analysis of the acquired data is necessary. In this sense, it is important to focus on the evolution of the operational conditions of the plant during the experiment. If there is a lot of a variation in the operational conditions during the execution of the experiment, this can get into problems during identification procedure. Although the active control keeps the rotor speed close to its rated value during the experiment, the high non linearity of the system with the pitch angle can make impossible to identify a reliable LTI model of the pitch loop.

For data coming from a simulation aeroelastic code, it is easy to see the incident wind. However, for data coming from real WT this could not be an option. However, there are several indirect measurements of the operational point which can be used. One of those is the gain evolution of the time varying controller during the experiment. This has been plotted in figure 21 for the length of developed experiments. It can be observed that, as was expected, for lower wind speeds there are large variations of the operating gain (however within the acceptable limits for the identification of a linear model) while for higher wind speed, like 24 m/s, the gain of the non linear controller is almost constant.

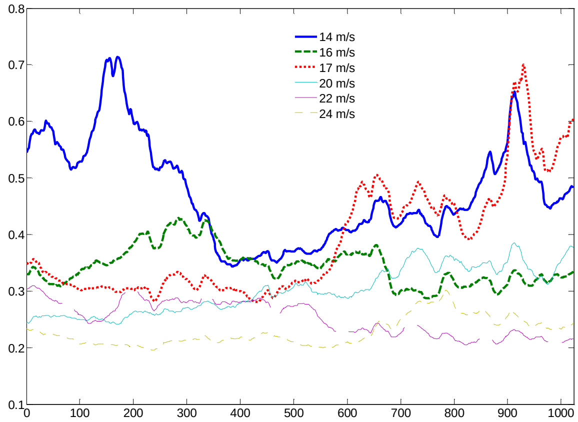


Figure 21: Gain variations during the set of closed loop identification experiments

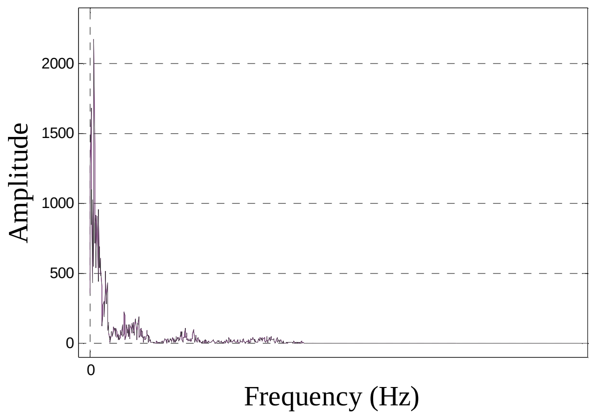


Figure 22: FFT for the measured generator speed for the identification case at 22m/s

It is also important to check the effect that the input excitation signal have had on the full WT. As it has been indicated before, only a few amount of energy is introduced in the system through this input signal. However, a wrong design of this signal 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 unpredicted 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 22**.** If a frequency correlation between the figure 22 and the WT component modes is done, it can be concluded that no dynamic amplification appears during the experiment. Then, the FFT content observed comes from the plant dynamics and the disturbances. Similar results can be obtained for all the identified cases.

3.5 Results

3.5.1 Algorithm Performance

The performance of the identification algorithms are usually evaluated first by so called “model validation techniques” which give clear indication if the identified models can be used for controller design. 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 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 the 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. Of course, it is possible to analyze the evolution of the covariance of each parameter. This will tell us if the experiment was enough long and if the frequency content of the excitation signal is enough “rich”. In figure 23 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.

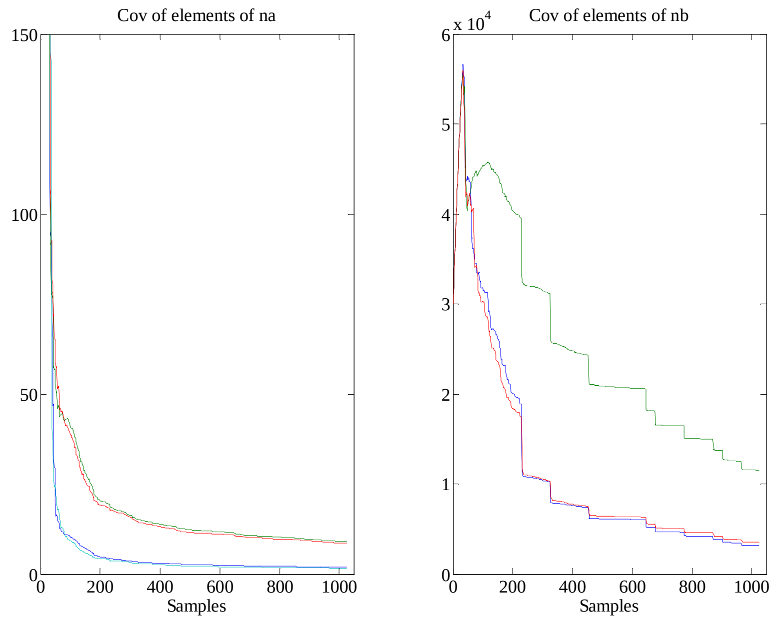


Figure 23: Covariance evolution of the identified parameters for the identification case at 14m/s

In figure 23, it can be observed how the element’s covariance decreases with the number of samples. 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 elements of the numerator is slower, although it seems that both numerator and denominator parameters converge towards a fixed value. From these plots, it can be considered to enlarge the length of the experiments in order to get a clear steady state convergence also for the parameters of the numerator of the plant transfer function.

3.5.2 Analysis of the identified Models

The models have been identified in closed loop while a non linear time varying controller is running and this was made possible by the use of the new algorithms described in Section 3.3. 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. The frequency characteristics are summarized in figure 24. Here it can be seen the non-linear effects coming from the different operational conditions. Important changes in dc gain are clear between the different models. At medium frequencies, in general, similar slopes are identified. However, probably the most relevant differences are at higher frequencies where important difference in the resonance and antiresonance are clearly shown in figure 24.

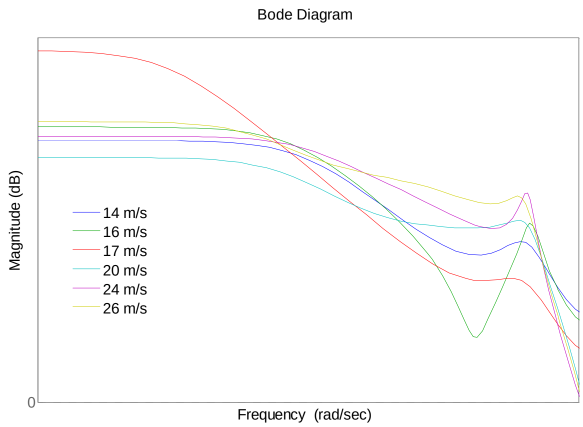


Figure 24: Models obtained supposing LTI controller in closed loop operation

This non linear behaviour of the system can also be illustrated in the poles –zeros map of three different models obtained at 14m/s, 16m/s and 17 m/s., figure 25. Here one can easily observe the well known property of the pitch plant which modifies fundamentally its dynamic properties depending on the operating wind speeds, which forces a change in pitch angle. 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 (below 16 m/s) to minimum phase (up from 17m/s)[1].

[1] Positive zeros outside the unit circle characterize non minimum phase behaviour while zeros inside the unit circle characterize minimum phase behaviour.

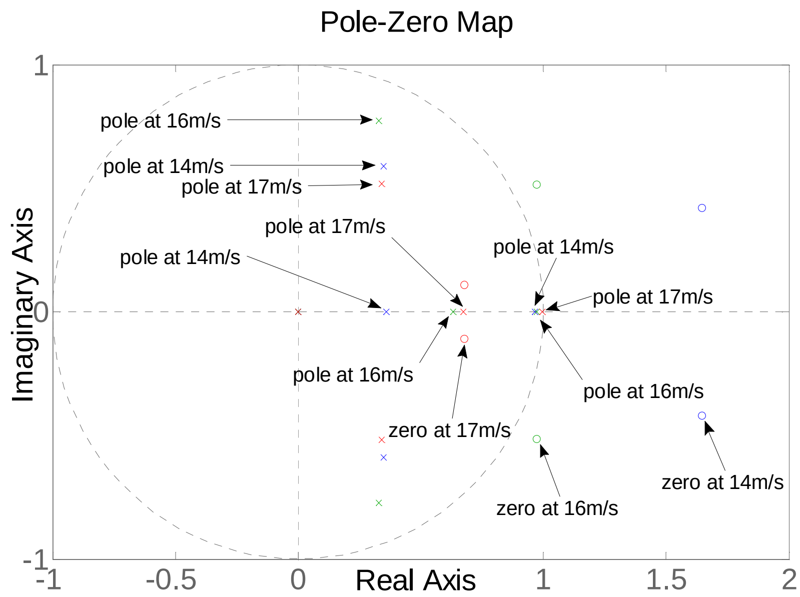


Figure 15: pole zero map for models which crosses from non-minimum phase to minimum phase plant depending on wind speed velocity

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 22. This was expected because the frequency analysis of the output didn't show any amplification of the drive train mode, and because the damper in the torque loop was active during the execution of the experiments. So, if these models should be compared with those coming from the linearization toolbox of the aeroelastic codes, (in this case Bladed®), this aspect should be taken into account.

In order to check the obtained model identified with the new algorithm, it has been compared with the model coming from the linearization tool from Bladed®. These models are plotted in figure 26, for the case of 16m/s wind. The frequency characteristic of the model identified with the new algorithm presented here is plotted with a solid line, while the frequency characteristic of the linearized model from Bladed® which includes the drive train damper is plotted with a dotted line. The two models look quite different. There are important deviations at low frequency, where a positive slope is found at the linearized model, while no dynamics are shown in the identified model at zero frequency. Some uncertainty should be added to the identified model since no input excitation signal is added at that frequency, and then the identified model is not totally trustful at this frequency range (but this has almost no impact for controller design). In addition, important deviations in gain plots are observed before the first pole is identified, where the slope changes to a negative value. At frequencies around 1 rad/sec, the slope and gain of both models look similar. After this point a lot of activity coming from the high order of the linearized model is clearly observed, and the two models doesn't look similar anymore. The order of the linearized model is about ten times higher than the order of the identified one, clearly too high for control design purposes. Some non observable modes, as well as not reliable low frequency dynamics coming from unrealistic linearization results are present in this linearized model. Since there are significant differences between these models, only the performances of the controllers designed on the basis of these models will tell us which is the best model for controller design.

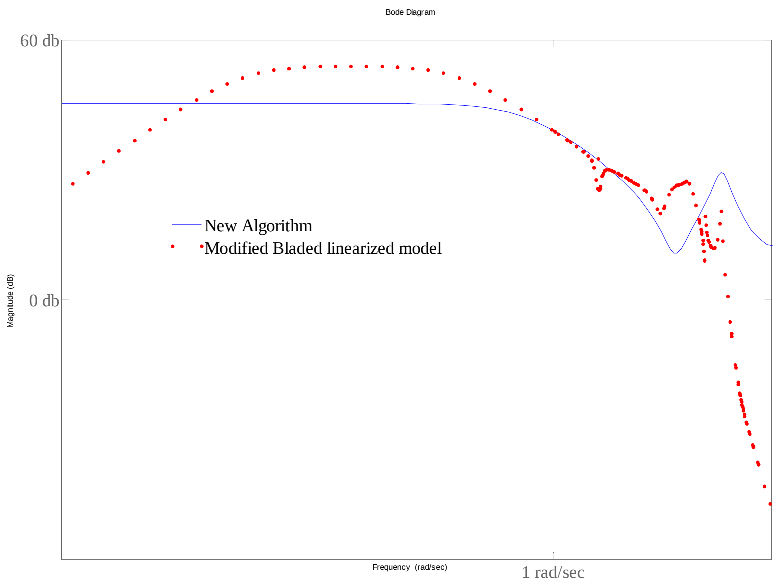


Figure 26: Linear models for 16 m/s wind speed identified with the new algorithm and the linearized model with damper

4. Experiments on CART2

Experiments on CART2 are expected to start on 2011, outside from the Up-Wind project, in collaboration with NREL and CENER.

5. Conclusions on WT closed loop Identification

Based on the obtained results, it can be concluded that Wind Turbine identification in closed loop operation is possible. However, important work must be taken into account and develop in two different frames:

- Wind Turbine experimental protocol
- Correct treatment of the experimental data

Although it has been proven in preliminary exercises on CART2 that it is easy to implement the experimental protocol for closed loop identification, it should be done taking into account smooth switching between normal operation, experimental protocol and going back to normal operation.

But the most critical area of the research related with identification of wind turbines operating in closed loop, is the use of adequate algorithms for system identification. In this research, it has been proof the goodness of CLOE family algorithms for this purpose, against classical open loop algorithms. However, it has also been proved that not all CLOE algorithms give valid models. The special characteristics of Wind Turbine dynamics makes that the most content in the output, the measured generator speed, or the rotor speed, comes from disturbances, and this a critical point for a correct identification.

It has been proved that identified models with constant wind speeds gives similar models to those obtained from the linearization tool from Bladed, and also to FAST, although not included in the report. Then, this technique can also be applied in the WT design procedure, since reliable linear model are obtained, but without problems coming from numerical errors from aeroelastic codes linearization routines.

Therefore the process of tuning the control loops in the commissioning procedure can be faster since identified linear models are now available. Even more, this new technique can bridge a gap in new control strategies for WT, like adaptive control, since on-line identification in real time of the plant can be obtained.

It is also possible to talk about control loop maintenance during WT life. It is important to see that this procedure can be executed on real time in the wind turbine, while Control Engineer is far from the WT. This could be an important advantage, for example in the field of offshore technology. The models identified in closed loop operation, with the knowledge in control tuning techniques will provide a powerful protocol to design in a shorter time a better controller.

It is important to point out that the challenge of providing reliable linear models are also important from the certainty of stability margins and robustness stability, which can not be tested against not reliable linear models. These linearized models from aeroelastic tools have been very useful from the initial design point of view. However this robustness analysis is difficult since these models are not enough reliable because of the always existing modelling mistakes and the linearized technique employed to compute the linear models.

In addition, the creation of a new algorithm which is able to identify pitch models while using non linear control structures like gain scheduling is also a big step for the identification of the main control loops of a Wind turbine. However, new validation tests should be developed for this algorithm. However, the performance of controllers designed based on identified models have demonstrated interesting results like the availability to control the full operating range of wind speeds with a robust linear controller based on these models, obtaining similar performance in terms of disturbance rejection, rotor speed regulation and pitch activity.

6. References

[1] Iribas M. Closed loop Identification for Wind Turbines. CENER Ref IN-08.00289. 2006.

[2] Burton T. Sharpe D. Jenkins N. Bossanyi E. Wind Energy Handbook. Wiley 2001.

[3] Iribas M., Landau I.D. Identification of wind turbines in closed loop operation in the presence of three dimensional turbulence wind speed. Wind Energy Journal 2009; 12:660-675.

[4] Iribas M., Landau I.D. Closed Loop Identification of Wind Turbines Models for Pitch Control. Mediterranean Control Conference 2009.

[5] Iribas M., Landau I.D. A New Algorithm for the Identification of Wind Turbines Models for Pitch Control in closed loop operation. Wind Energy Journal. Under Revision.