Closed Loop Identification of Wind Turbines Models for Pitch Control

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Abstract— **In order to design a model based controller availability of a linear model of the system to be controlled is mandatory. Open loop identification is a very well known and extended used technique which provides reliable linear models for control design purposes. However, classical open loop identification techniques can not be applied to the case of wind turbines for several reasons: operating in open loop could render the system unstable, the aerodynamics are non-linear, the wind input disturbance can not be measured and it has an important stochastic component and finally, the measured data are normally corrupted by disturbances and noise. This article presents a procedure allowing wind turbine identification in closed loop operation with time varying controllers. A set of reliable linear models for control design of the pitch loop are obtained.**

I. Introduction

Substantial efforts in modelling Wind Turbines (WT) have been done during the last decades [1]. Different approaches have been considered in fields like aerodynamics, mechanical modelling, electrical models, etc. Based on these researches, some advanced WT simulation tools have been developed like [2], [3], [4]. Such aeroelastic simulators have demonstrated to be a good tool for WT design, showing a good correlation between simulated and real measurements for both extreme and fatigue mechanical loads. However, these simulation tools are not fully useful for control engineers since they were not able to provide reliable linear models for control design.

New developments were performed some years ago with different numerical procedures to obtain linear models from the aero-elastic simulators. The use of such linearized models describing the WT dynamics was a real breakthrough, since these gave the opportunity to perform model based analysis and control. However, linearized models present some drawbacks:

- They do not always converge to a (periodic) steady state solution.
- The order of the resulting models is unnecessarily high for describing the plant dynamics, including non-observable modes.
- Numerical errors caused by linearization techniques introduce unrealistic dynamics, especially at low frequencies. This is especially noticeable in phase plots.

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- Methods based on linearization do not provide any insight about the real dynamics occurring in a WT at each site. A wrong parameterization of the theoretical models or deviations stemming from the manufacturing process can enlarge the gap between theoretical model and real dynamic behaviour of the WT.

The control used in the WT design process is crucial from the generated WT loads. The appearance of these modeling problems makes these controllers behavior unsatisfactory or even in some cases unstable. Then, it is very common to have a controller designed based on these linearized models which cannot be used on the real WT. Nowadays this problem is somehow solved by a trial and error tuning of the controllers for each WT.

Open loop system identification has been extensively used in order to overcome the problem of hand tuning of the controllers, leading to reliable numerical linear models for model based control design [5]. The use of classical open loop identification techniques are probably not a good choice for WTs because operating in open loop during a system identification experiment can render the WT unstable. Taking into account this risk, the use of identification techniques in closed loop operation seems a good choice since it guarantees the safety and integrity of the WT at any wind speed condition.

In section II, a brief review of previous approaches in the frame of identification of WT is presented. In section III the physical model of the pitch loop, as well as a classical control scheme used and the design of the identification experiments are discussed. In section IV, the identification algorithm solution for the pitch loop using a time varying controller is introduced (this is a new algorithm in the field of identification in closed loop). Identified models obtained at different wind speeds are presented and analyzed. Concluding remarks and future extensions of this research are presented in Section V.

II. Previous approaches

A very well known technique for obtaining reliable linear models for control design purposes is system identification [5]. The main idea of this technique is based on introducing a persistent excitation signal into the system by having access to the energy source of the system. Then, treating the input and output data, and using a correct identification algorithm, a linear model is obtained. The obtained linear model should be validated in a later step. However, the application of standard open loop system identification techniques for the identification of WT is hampered by several factors:

- Operating in open loop can render the WT unstable.
- The highly non-linear behaviour of the WT with the wind speeds.
- Since the power source of the system, the wind, is not under control, it is not possible to fix a desired operational point for the experiment.
- Wind disturbances, which exhibit an important stochastic behaviour, can not be measured.

Operating in closed loops guarantees the stability of the WT, even if the behavior is not as good as desired for an initial controller. In addition, operating in closed loop makes the system to work around an operation point, which facilitates the task of obtaining a dynamic linear model. Furthermore, it opens up the possibility of obtaining a relevant linear model for control design when the initial controller fails to achieve the expected performances. Identified models can help to a better on site controller tuning. Even more, it was experimentally proven, e.g. [8] [9], that if the objective is to identify a model for control design, models identified in closed loop operation with appropriate algorithms are better in terms of control performance than models identified in open loop. Of course, identified models are in general better than numerically linearized models for the purpose of controller tuning.

Previous works which are somehow related with the field of WT and system identification exist, but they usually look for models which are not dedicated primarily for control purposes. In [10], an experimental approach conceived to determine the aeroelastic damping of a WT is introduced. In [11] [12], the identification is divided between a linear model, for drive train identification, and a non-linear model accounting for aerodynamic effects, with extra measurements. In [13], a full transfer function from torque demand to generator speed is obtained based on open loop identification algorithms. Newer developments in the field of system identification have been applied to WT closed loop identification. Then, in [14] the linear parameter varying identification on repetitive sequences and subspace identification in closed loop has been applied to a WT However quite long experiments are required which may be a serious problem in practice.

A closer solution to the one proposed in this paper for identification of wind turbines in closed loop operation for control design purposes was presented in [15]. However, this work deals with a solution for constant wind speed, which is intrinsically a big limitation for the identification of a real WT. The solution adopted in [15] can not be applied in the presence of three-dimensionally turbulent wind flows

In [16] a new development for identification of the torque loop in the presence of three dimensional turbulent wind speed was presented and successfully applied. This is of special interest for the design of the drive train damper control algorithms in a variable speed WT [1].

This research aiming at the identification of the pitch loop is a natural extension of the work developed in [16] for the torque loop. However, the algorithm used in [16] cannot be applied because the most common pitch control loops use non-linear time varying controllers. Therefore a specific new algorithm has to be developed.

III. PITCH LOOP DESCRIPTION

A. *Physical model*

Pitch loop dynamics are complex. On one hand the coupling between the non-linear aerodynamics with the flexible structural dynamics of the blades and tower are critical for understanding the dynamic behavior of the pitch loop. This coupling with the flexible structures makes the system of non-minimum phase at certain wind speeds, [21]. On the other hand, it is also important to take into account the drive train and the generator dynamics, as well as the pitch actuator and the transducers.

For variable speed wind turbines, the drive train is slightly damped because the torque in the drive train doesn’t change with the generator speed. This problem is usually solved in the torque loop by control, [1]. This control solution has a strong effect on the pitch loop dynamics, and should be taken into account while doing the identification of the pitch loop.

Although the modeling of some of this features is complicated, like aerodynamics and flexible structures, others are easier to characterize, and are also critical. These are for example the transducer, the generator response or the pitch actuator, which can be described by a first or second order linear model. It is important to point out that the gain of the model is negative, which is important since this introduces a 180 phase in the system which should be taken into account.

For variable speed WT configuration, the pitch control loop is active at 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 reducing mechanical loads as much as possible. The control direction depends on the full WT configuration, [1]. Some WT move the pitch angle to feathering and others to stall. 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 pitch angle and the aerodynamical forces. If the pitch angle increases in this range, the aerodynamical forces decrease. Normally, the control loop is designed in order to operate at this linear range, avoiding problems coming from stall values, at higher angles of attack, where higher uncertainties appear and linearity disappears.

B. Classical control loop for variable speed WT

There are different ways of controlling the pitch loop, with different control structures and of course different methodologies can be used for designing the controllers. However, there are some common characteristics of the control schemes for the pitch loop, since they all have to solve similar problems. A very well known pitch loop control scheme is depicted in Figure 1. The selected control scheme is one of the most used in the industry for the pitch loop control.

There are some very well known physical effects on the dynamic behaviour of a WT like the tower shadow, the wind shear, gravity loads, misaligned rotor and unbalanced rotor, which provokes strong and narrow band disturbances (C/D), in the measured generator speed in the pitch loop. These strong and narrow band disturbances are mainly the well known *nP* disturbances, *n* being an integer and *P* the frequency of the rotor. The frequency of *1P* disturbance corresponds to the time needed for one blade to complete one revolution. The use of notch filters (N/M), in the feedback loop is common to most of the schemes used in practice, see Figure 1. The objective of these notch filters is to eliminate from the measured generator speed the frequency content coming from these specific disturbances. While no special control design for attenuating these disturbances is employed, it is mandatory to filter them in order to avoid their amplification and WT instability.

Once the strongest disturbances are removed from the measured generator speed, a linear controller (R/S) is commonly used, see Figure 1. The well known nonlinear relationship between the extracted power from the wind, P, and the wind speed, V, is given in eq.1. In addition, the extracted power is linear with the area of the rotor characterized by the blade's radio, R. The term Cp in eq.1 deals with the characterization of the aerodynamical profiles of the blades and the power which can be extracted from the wind, depending on the wind speed, blade's pitch angle, β, and rotor speed.

$$P = \frac{1}{2}\pi R^2 C_p V^3 \qquad (1)$$

Assuming this high nonlinearity and the level of uncertainty of the existing models representing the WT aerodynamics, a time varying controller (TVC), based on indirect measurements of wind speed is commonly used, see Figure 1.

The wind has a time varying magnitude with different energy content at low and high frequencies. The low frequency content is relatively deterministic and depends on the season, synoptic and daily events. However, important stochastic high frequency content is also present in the wind speed. In addition, the rotating blades induce a high level of turbulence in the inflow which can provoke different wind speeds and directions at each point of the rotor plane. For this reason no reliable wind speed measurement is nowadays available for using it in any feedback or feedforward control loop.

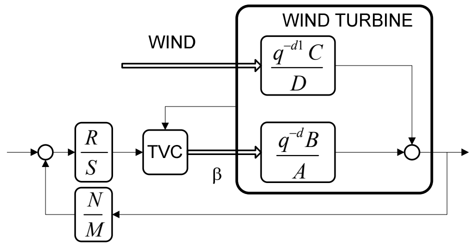


Figure 1. Classical pitch control loop

C. Experimental Data

The experimental procedure for obtaining data was introduced in [16]. The procedure is quite similar to the one used in open loop identification [5], except for the fact the experiment is done in closed loop operation. Basically it consists in adding an external excitation signal at the output of the controller, and recording the controlled measured output (in this case, the generator speed). It is also possible to introduce the excitation signal at the reference. The location where this input excitation signal is added is important for two reasons: on one hand, because it affects the design of the excitation signal, and on the other hand because of the parameterization of the closed loop identification algorithm, since different sensitivity transfer functions will be optimally estimated together with the plant model.

The design of the input excitation signal is critical for a correct identification of the plant. This input should be shaped in both, magnitude and frequency. It is important also to realize that the introduction of nonlinearities in the path to be identified must be avoided. In this sense, it is important to avoid input excitation signals which saturate the pitch actuator, in speed or in acceleration. It is also important to avoid during the identification experiment the excitation of undamped modes, like the drive train, or structural modes like tower or blades modes (these excitations can lead to the instability of the WT). Therefore, one should be cautious with the magnitude of the input excitation at these frequencies. However, a too small amount of energy at a certain frequency, would probably avoid its correct identification. It is important to realize at this point that shaping energy content in high frequency will be limited by two factors: the pitch actuator saturation limits and the sampling frequency of the pitch loop. Then, if the actuator is not designed to effectively operate above some frequency, it will not be possible to identify correctly this frequency range. However, the pitch actuator is usually designed according to the needs of the WT, so it is supposed that it will be possible to have enough energy at the highest frequencies of interest for control purposes. Furthermore, it is easy to understand that the identification of low frequencies will be limited to the length of the experiment.

Since no energy is introduced below the corresponding frequency to the half of the time length of the experiment, no trustful identification is possible below this frequency. However, taking into account the nonstationarity of the wind, too long experiments may not be useful since the turbulence wind would change the operating point during the experiment and would reduce the significance of the identified model. In addition, since controllers incorporate an integrator, the exact characteristics of the WT at very low frequencies may not be crucial.

The design of the input excitation signal should then be considered with care, and preliminary trials on simulation tools before trying it in a real WT should be considered. Based on the experiments carried out in one non-linear model based on the software Bladed® [3], a good input excitation signal based on a filtered PRBS has been found. The duration of the experiment is 54 seconds with a total number of 1080 samples. One example of input excitation signal is shown in Figure 2, for the case of identification at 26m/s wind speed. However, it is probable that a longer experiment would be needed in a real WT because of the presence of lower signal/noise ratios.

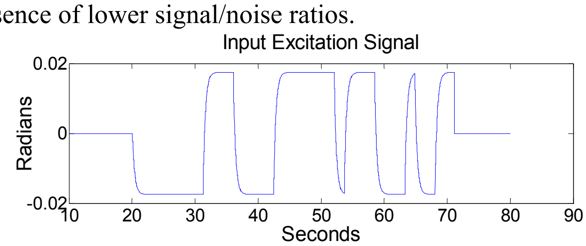


Figure 2. Input excitation signal, for the case of 26 m/s.

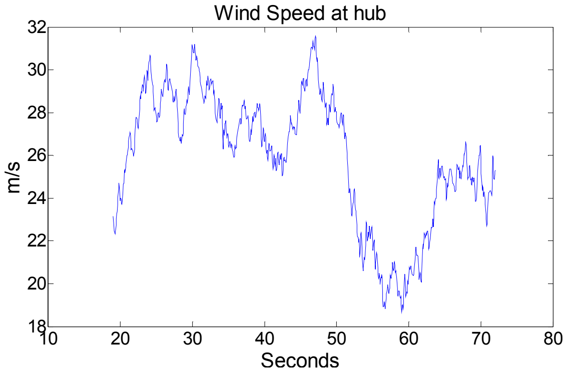
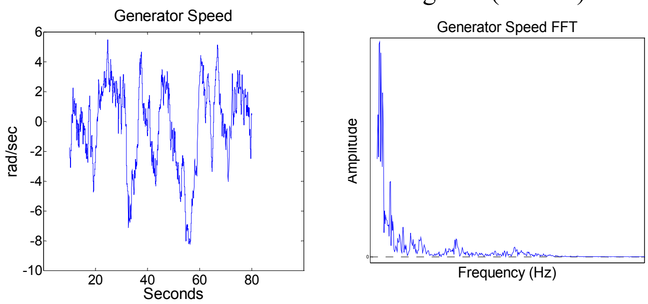


Figure 3. Wind Speed at hub position, for the case of 26 m/s, during the application of the external excitation signal.

Taking into account that linear models at various wind speed are needed in order to design the pitch control loop, several identification experiments have been carried on at different wind speeds. For these simulations, winds according to standard IEC 61400-1 have been used, trying to get situations as close as possible to real operating conditions. Then, experimental data for a three bladed, upwind, multi-MW, variable speed, pitch to feathering controlled and double feed induction generator WT have been obtained on the basis of the Bladed® simulation tool. Several experiments based on the scheme given in Figure 1 where developed. The mean speed during this experiments were: 14m/s, 16 m/s, 17 m/s, 20 m/s, 24 m/s, 26 m/s. The only restriction that was taken was that the pitch controller should be active during the experiment.

Once the experiments are implemented, the only measurement taken from the WT is the measured generator speed. This is all the information which needs to be measured in order to carry out the identification of the WT. The measured generator speed and its frequency content for the case of 26m/s can be observed in Figure 4(a and b).



(a) (b)

Figure 4. (a) Variations of measured generator speed over its demanded value, for the case of 26 m/s. (b) FFT of measured generator speed in normalized frequency range, for the case of 26 m/s.

IV. ADOPTED SOLUTION

A. *Algorithm for identification of Pitch Loop in closed loop operation*

The algorithm developed for the identification of the Pitch Plant, shown in Figure 5, is an extension of CLOE family algorithms for the case of time varying controllers. The objective of CLOE algorithms is to identify a plant that in feedback with the actual controller, gives a sensitivity transfer function as close as possible to the real operating one. Suppose the real, Ω, and estimated, $\hat{\Omega}$, generator speed are given by, eq. 2 and eq. 3, where β is the pitch angle, e is white noise and ε the predicted error:

$$\Omega(t) = \frac{z^{-d} B(q^{-1})}{A(q^{-1})}\beta(t) + \frac{z^{-d1} C(q^{-1})}{D(q^{-1})} e(t+1) \tag{2}$$

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

where:

$$A(q^{-1}) = 1 + a_1 q^{-1} + \ldots + a_{nA} q^{-nA} \tag{4}$$

$$B(q^{-1}) = b_1 q^{-1} + \ldots + b_{nB} q^{-nB} \tag{5}$$

$$\hat{A}(q^{-1}) = 1 + \hat{a}_1 q^{-1} + \ldots + \hat{a}_{nA} q^{-nA} \tag{6}$$

$$\hat{B}(q^{-1}) = \hat{b}_1 q^{-1} + \ldots + \hat{b}_{nB} q^{-nB} \tag{7}$$

The real measured output of the system, eq.2, and the estimated plant, eq.3, are used to compute the closed loop error ε. This quantity is used by the Parameter Adaptation Algorithm (PAA), which recursively estimates the parameters of the plant. Note that identical controllers are used in the true loop and in the loop containing the estimated plant model.

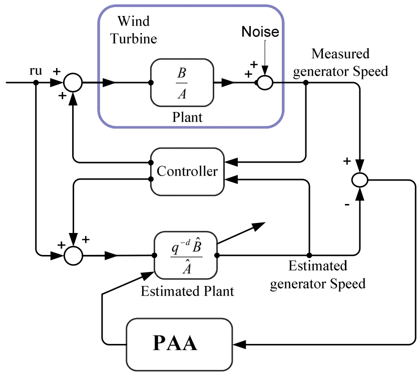


Figure 5. Identification algorithm scheme for pitch loop model identification

The estimated parameters can be arranged in a vector of parameters θ, to be estimated. The measurements from the estimated closed loop can also be arranged in a measurements vector, Φ, and used in the PAA. The PAA algorithm is defined by equations 8 to 11. For details on PAA, see [6] and [25].

$$\hat{\theta}(t+1) = \hat{\theta}(t) + F(t)\,\phi(t)\,\varepsilon(t+1) \tag{8}$$

$$\varepsilon(t+1) = \frac{\varepsilon^0(t+1)}{1+\phi^T(t)\,F(t)\,\phi(t)} \tag{9}$$

$$\varepsilon^0(t+1) = w_1(t+1) - \hat{\theta}(t)\,\phi(t) \tag{10}$$

$$F(t+1) = \frac{1}{\lambda_1(t)}\left[F(t) - \frac{F(t)\,\phi(t)\,\phi^T(t)\,F(t)}{\frac{\lambda_1(t)}{\lambda_2(t)} + \phi^T(t)\,F(t)\,\phi(t)}\right] \tag{11}$$

B. *Obtained Models*

The frequency characteristics of the identified models at different turbulent wind speeds are plotted in Figure 6. As expected, there are some differences for the DC gain of the different models. However, taking into account the length of the experiments, 54 seconds, this gain should be treated with care.

In Figure 6 it can also be observed that there is an undamped mode at around 20 rad/sec. This resonance corresponds to one of the rotor modes. And it is also clear that at 10 rad/sec appears an anti-resonant mode (a pair of complex zeros), which is less damped at low wind speed. At frequencies between the 0 frequency and the anti-resonance all models have a similar slope, except for the case of 17m/s.

C. *Analysis of the obtained models*

The main important characteristic that can be observed from the obtained models is that they have similar frequency patterns. However important differences in the zeros map occur and this must be analyzed. Actually this difference was expected based on the physical knowledge of the pitch loop, [22]. It can clearly be observed in the pole zero map of the models at 14, 16 and 17 m/s, (Figure 7), how a pair of complex unstable, non minimum phase zeros move to stable zeros (minimum phase zeros) at 17 m/s. This can also be seen on the frequency characteristic of Figure 6, where the anti-resonance in the model at 16m/s is quite strong (low damped). The detection of this behavior would lead to a more advanced control scheme. Such a scheme will take into account that the system at high wind speeds is moving from non-minimum to minimum phase, and then, the bandwidth of the system can be increased. This will allow improving the performance of the pitch loop at higher wind speed, where major loads occur.

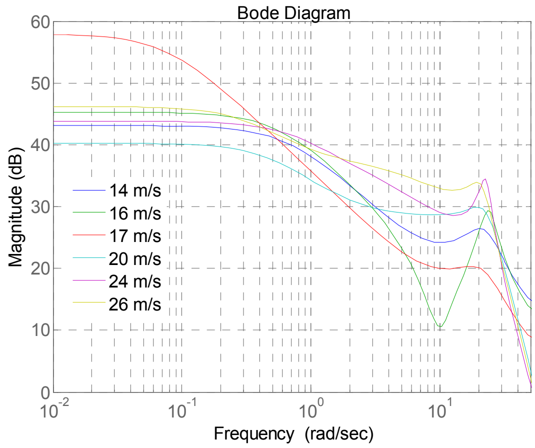


Figure 6. Bode's magnitude diagram for the identified models at 14, 16, 17, 20, 24 and 26 m/s turbulence wind speeds

Some differences are also present at the DC gain of the models. This was also expected because of the influence of the wind speed with the DC gain of the pitch loop. The model at 17m/s shows a big discrepancy for the DC gain. It is also important to note that at this wind speed, the slope between the lowest frequencies and the anti-resonance is different from the other models. In Figure 8, the behavior of the controller's nonlinear parameter (gain) during the experiments can be observed. At 17m/s, two well defined regions of values are easily detected. Taking into account the important change in the dynamics that occur around this wind speed, this model should be treated with care, and probably more models should be identified at wind speed close to 17m/s in order to extract a correct conclusion.

It can be observed in Figure 8 that not all the experiments have the same range of non-linear behavior of the time varying controller. Actually, in experiments at high wind speeds like 24 or 26 m/s the parameter variations are really small. This can be justified by the evolution of the wind excursions during the execution of each experiment. Small variations on controller's parameter would mean that the system in that case is linear or soft non linear. However, for lower wind speeds, the range of variation of this non linear parameter during the experiments is much higher.

The use of this time varying controller makes useless the realization of any statistical validation of the identified models. No validation method has been yet developed for the validation of the obtained models since the closed loop system is non linear and time variant (statistical tests and transfer function comparisons in closed loop can not be used in this case). The next step in this research will be to look for a validation test in closed loop identification when using a time varying controller. The only true validation of the model can be done only a posteriori by looking to the control performances obtained with a controller designed on the basis of models identified in closed loop operation.

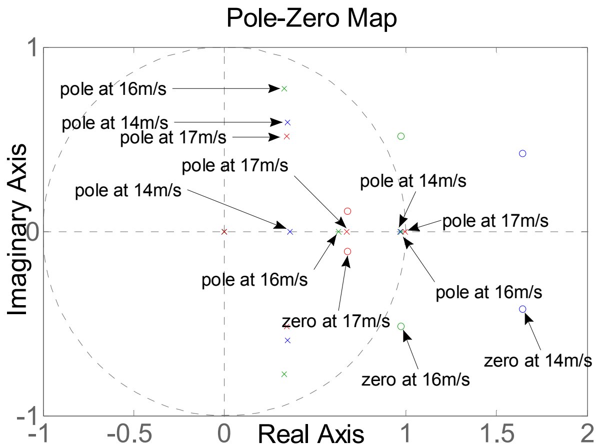


Figure 7. Pole – zero map of identified models at the transition from non-minimum phase to minimum phase wind speeds.

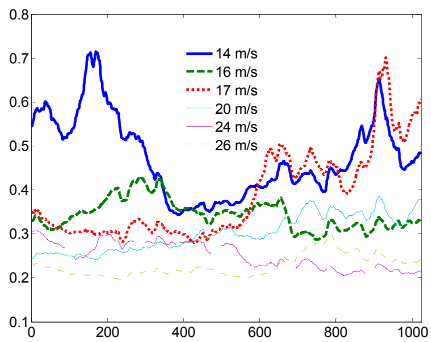


Figure 8. Variations of the non linear gain during the experiments.

V. Conclusions and Future Work

A new algorithm for obtaining linear models from experimental data from the pitch loop of a WT has been introduced. This algorithm overcomes the problem of the use of a time varying non linear controller, leading to LTI plant models. The obtained models indicate a strong correlation between physical models and identified models, in the sense that they show the transition from non-minimum to minimum phase behavior as the wind speed increases. The impossibility of applying classical closed loop model validation tests has been explained. Further work should focus on developing validation tests for the model identified in closed loop with a time varying controller. Future developments should also move to the identification of MIMO systems in the frame of individual pitch control. Another challenge is the replacement of a time varying controller by a linear robust controller and comparative evaluation of the two approaches.

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