USE OF STATE-SPACE MODELING TO EVALUATE AND CONTROL THE MODE SHAPES OF A LARGE-SCALE WIND TURBINE

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Abstract— In this paper, an application of control-structure interaction is presented. The wind turbines are complex systems, subjected to random wind loads, and with large and flexible components. One of the main functions of pitch control system is to regulate rotor speed in rated operation conditions and mitigate the dynamic loads in the mode shapes of the turbine. However, as a flexible structure, the characterization of the mode shapes influences in the aerodynamic forces on the rotor blades, changing also the rotor speed characteristics. In this regard, the mode shapes behavior can provoke oscillations in rotor speed control, due to the coupled dynamics. In this work, a state-space modeling is proposed to identify which are the problematic mode shapes and to cope with the wind turbine fully coupled dynamics.

Keywords— Wind turbines, Structural dynamics, State-space control, mode shapes

Resumo— Neste artigo, é apresentada uma aplicação de interação controle-estrutura. As turbinas eólicas são sistemas complexos, sujeitos a cargas de vento aleatórias e com pás grandes e flexíveis. Uma das principais funções do sistema de controle de passo é regular a velocidade do rotor em condições de operação nominais e mitigar as cargas dinâmicas nos modos de vibração da turbina. No entanto, como uma estrutura flexível, a caracterização dos modos de vibração influencia as forças aerodinâmicas nas pás do rotor, alterando também as características da velocidade do mesmo. A este respeito, o comportamento dos modos de vibração pode provocar oscilações no controle da velocidade do rotor, devido à dinâmica acoplada. Assim, neste artigo, propõe-se uma modelagem em espaço de estados para identificar quais são os modos de vibração problemáticos e para lidar com a dinâmica completamente acoplada da turbina eólica.

Palavras-chave— Turbinas eólicas, Dinâmica estrutural, Controle em espaço de estados, modos de vibração.

1 Introduction

In the last decades, the wind energy has been frequently pointed as one of the possible solutions to the environmental crisis. This is the why there has been a strong technological development in this field, with wind turbines reaching over 100 m of rotor diameters and 120 m of tower height. The control technology was fundamental to these advancements, and the control systems are an integrating part of the modern wind energy conversion systems (Pao and Johnson, 2011).

Wind turbines have three main control systems: the pitch control, the generator torque control and the yaw control. These are responsible for specific functions. Pitch control regulates the blades pitch angle in order to control rotor speed and loads. Generator torque control controls rotor speed in sub-rated operation to ensure maximum aerodynamic efficiency. Yaw control is responsible for tracking the wind speed direction changes by controlling the position of the wind turbine nacelle. The main wind turbine components are presented in Figure 1.

These control systems play a key role in reducing the wind turbine cost-of-energy (COE) by a two-fold path: they help to increase power production and to reduce wind turbine loads. Both measures generate an optimized power production and a reduced components cost, respectively. The reduction of COE is a fundamental variable to increase wind energy competitiveness and improve its cost-effectiveness related to the conventional power sources such as coal and gas (Novaes Menezes, Araújo and Bouchonneau da Silva, 2018).

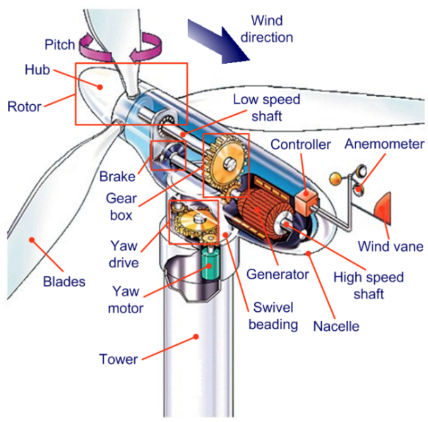

Figure 1: Wind turbine main components

Amongst the control systems, the most researched development relies on pitch control to reduce wind turbine loads. The pursuit for reduced COE has pushed wind turbines to more flexible and bigger designs, which can suffer from stability problems and increased aerodynamic and elastic loads. In this regard, the pitch control can be used to reduce the loads by influencing all the wind turbine dynamics and at the same time controlling rotor speed at the rated value. To achieve this, the pitch control needs to use a state-space modeling to master various wind turbine variables. By doing so, it is possible to add damping to the mode shapes of the structure and accordingly reduce mechanical loads.

In this paper, a state-space modeling is used to evaluate the wind turbine mode shapes dynamic stability and to reduce specific wind turbine structure oscillations. The model is presented for a large scale machine, the NREL 5 MW reference wind turbine (Jonkman et al., 2009.).

2 Wind turbine dynamic modeling

2.1 State-space and modal analysis

In order to analyze and control wind turbine dynamics, a suitable mathematical model must be developed. The dynamics of a structure can be modeled using the finite element method, the multibody dynamics method and the modal analysis. The later is the most recommended for control purposes, since it can be transformed in a state-space modeling. The nonlinear equations of the wind turbine are represented by:

$$\mathbf{M}(q,u,t)\ddot{q} + \mathbf{f}(q,\dot{q},u,u_d,t) = 0 \tag{1}$$

which form a set of several differential equations. These equations need to be linearized in order to run classical modal analysis. The linearization is performed under the operation point:

$$v = 16\,\mathrm{m/s}; \quad \Omega_0 = 12.1\,\mathrm{rpm}; \quad \beta_0 = 0.2105\,\mathrm{rad}$$

where v is the wind speed, Ω_0 is the rotor speed and β_0 is the pitch angle. These values of operating point were already used in previous works (Raach et al., 2014) and place the wind turbine in the desired operation mode (above-rated operation). After linearization, the wind turbine dynamics equations become:

$$\mathbf{M}\Delta\ddot{q} + \mathbf{C}\Delta\dot{q} + \mathbf{K}\Delta q = \mathbf{F}\Delta u + \mathbf{F_d}\Delta u_d \tag{2}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively, and q, u and u_d are respectively the degrees of freedom (DOFs) in which the structure is linearized, the control inputs and the disturbance inputs. $\mathbf{F}$ and $\mathbf{F_d}$ are the forcing matrices and Δ stands for perturbed variables.

This model is not still the desired state-space modeling; to achieve it, one must replace the perturbed DOFs vectors $(\Delta\ddot{q}, \Delta\dot{q}, \Delta q)$ by the state vector x and $\dot{x}$:

$$x = \begin{bmatrix}\Delta q \\ \Delta\dot{q}\end{bmatrix}; \quad \dot{x} = \begin{bmatrix}\Delta\dot{q} \\ \Delta\ddot{q}\end{bmatrix} \tag{3}$$

Thus, the system is represented in the state-space by:

$$\dot{x} = \mathbf{A}x + \mathbf{B}\Delta u + \mathbf{B_d}\Delta u_d \tag{4}$$

$$y = \mathbf{C}x + \mathbf{D}\Delta u + \mathbf{D_d}\Delta u_d \tag{5}$$

where $\mathbf{A}$ is the state matrix, $\mathbf{B}$ is the control vector, $\mathbf{B_d}$ is the disturbance vector, and $\mathbf{C}$, $\mathbf{D}$ and $\mathbf{D_d}$ are the output matrices.

2.2 Modeling software

To run the simulations and obtain the modeling described in the previous section, a specialized modeling software is required. In fact, the wind turbines have an intrinsic complexity which together with the complexity of its primary input, the wind, requires the utilization of detailed models to be simulated (Manwell et al., 2010). For this sake, the aero-servo-elastic codes are utilized.

These are simulation tools that incorporate sophisticated models of both turbulent and deterministic wind inflow; aerodynamic, gravitational, and inertial loading of the rotor; elastic effects within and between components; and mechanical actuation and electrical responses of the generator and of the control and protection systems (Jonkman, 2007).

In this paper, it will be utilized the software FAST, freely provided by the National Renewable Energy Laboratory (NREL) of the U.S. government. FAST has been validated and certified for wind turbine design and analysis (Manjock, 2005).

FAST uses the desired modal approach, modeling the turbine as a multi-degree of freedom system. Each DOF is associated with a specific mode shape of the turbine to be analyzed. FAST also allows to obtain the representation in state-space changing the perturbed DOFs vectors by the state vector as described in (3).

Further, it can run in mode simulation or in mode linearization, to obtain the matrices in (2), (4) and (5) under the desired operation point. Table 1 shows the DOFs modeled in FAST.

Table 1: DOFs of wind turbines modeled in FAST

Var	Description
q_1	Blade 1 flapwise tip displacement for mode 1
q_2	Blade 2 flapwise tip displacement for mode 1
q_3	Blade 3 flapwise tip displacement for mode 1
q_4	Azimuth angle, rotor side
q_5	Azimuth angle, generator side
q_6	Nacelle yaw angle
q_7	Fore-aft tower top displacement for mode 1
q_8	Side-aft tower top displacement for mode 1
q_9	Fore-aft tower top displacement for mode 2
q_{10}	Side-aft tower top displacement for mode 2
q_{11}	Blade 1 flapwise tip displacement for mode 2
q_{12}	Blade 2 flapwise tip displacement for mode 2
q_{13}	Blade 3 flapwise tip displacement for mode 2
q_{14}	Blade 1 edgewise tip displacement for mode 1
q_{15}	Blade 2 edgewise tip displacement for mode 1
q_{16}	Blade 3 edgewise tip displacement for mode 1

All simulations conducted in this work, used the wind time series shown in Figure 2, varying largely around, and not only on the operational point, to ensure the robustness of the control. The wind speed begins in $v = 14\,\mathrm{m/s}$ and reaches $v = 20\,\mathrm{m/s}$:

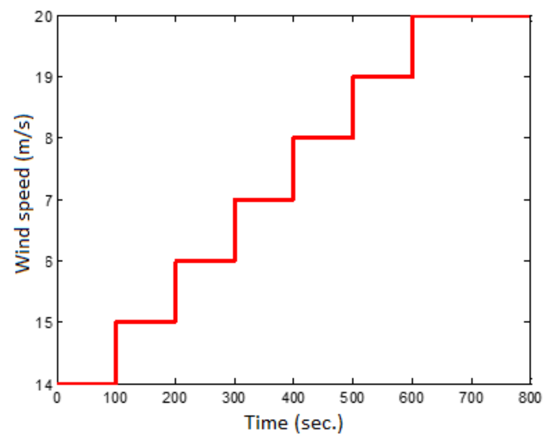

Figure 2: Simulated wind time series

2.3 NREL 5 MW *reference wind turbine*

The turbine utilized in this paper is a reference model created by the NREL to purposes of scientific research. Indeed, the commercial wind turbines have their detailed design protected by confidentiality issues, making infeasible to use those as research models. On other hand, the NREL 5 MW is a large-scale turbine with all the detailed design available and so it is largely used in research works (Yu and Kwon, 2014; Zhu et al., 2014). The main design specifications of NREL 5 MW reference turbine are described in Table 2.

Table 2: Specifications of the NREL 5 MW reference wind turbine (Jonkman et al., 2009).

Rating	5 MW
Rotor Orientation	Upwind
Rotor Configuration	3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor Diameter	126 m
Hub Diameter	3 m
Hub Height	90 m
Cut-In Wind Speed	3 m/s
Rated Wind Speed	11.4 m/s
Cut-Out Wind Speed	25 m/s
Cut-In Rotor Speed	6.9 m/s
Rated Rotor Speed	12.1 m/s
Rated Tip Speed	80 m/s
Overhang	5 m
Shaft Tilt	5 °
Precone	2.5 °
Rotor Mass	110.000 kg
Nacelle Mass	240.000 kg
Tower Mass	347.460 kg
Coordinate Location of overall CM	(−0.2 m,0.0 m,64.0 m)

3 Standard control of wind turbines and stability problems

In opposition to the state-space modeling used in this paper, the standard control of commercial wind turbines relies on a traditional PID control (Munteanu et al., 2008). One of the reasons is the apparently simplicity and the easy adjust of control gains after usually a small number of iterations (Bossanyi et al., 2013). On the other hand, the use of PID control can generate stability problems that must be addressed using filters (Wright, 2004).

These stability problems are caused due to the fully-coupled wind turbine dynamics (Leithead and Dominguez, 2006). In fact, as a multi-degree of freedom system, the pitch control that was designed without considering the whole structural dynamics can cause undesired oscillations or even instability in the unmodeled modes.

The standard control of wind turbines based on PID considers only one DOF of the system, the rotor azimuth, and the control action is formulated according to the error of rotor speed:

$$\Delta\theta = K_p \Delta\Omega + K_i \int \Delta\Omega(t)dt + K_d \Delta\dot{\Omega} \qquad (6)$$

Transforming by Laplace and using the matrices **A**, **B** and **C** from the state-space model, for a single input-output system it is obtained:

$$\frac{\Delta\Omega(s)}{\Delta w(s)} = \frac{\mathbf{B_d}s}{1 - \mathbf{B}K_d s + (-\mathbf{A} - \mathbf{B}K_p)s + (-\mathbf{B}K_i)}$$

The size of matrices **A**, **B** and **C** depends on the number of states considered which is related to the DOFs being modeled. In this case only a variable is being considered (rotor speed), then the matrices has size one.

According to most of authors, in commercial wind turbines the derivative term is usually set to zero, $K_d = 0$ (Hansen et al., 2005). Expressing K_p and K_i in terms of K_d, results:

$$\begin{aligned} K_p &= -\frac{A}{B} - \frac{2\zeta\omega_n(1 - BK_d)}{B} \\ K_i &= \frac{-\omega_n^2(1 - BK_d)}{B} \end{aligned}$$

The values of A and B are obtained from the linearization procedure of FAST and ω_n and ζ are respectively the frequency and the damping coefficient of the controlled system. Following the recommendations of the Danish National Laboratory RISØ and the NREL, these values are assumed to be $\omega_n = 0.6\,\mathrm{rad/s}$ and $\zeta = 1$.

To verify this control design, simulation was carried out in the integrated environment FAST/Simulink with only 1-degree of freedom enabled, the rotor speed, which was obtained through rotor azimuth derivative. Results are shown in Figure 3.

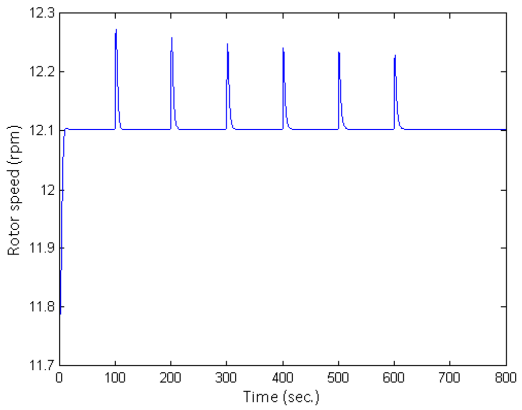

Figure 3: Rotor speed control, 1-DOF enabled for $K_p = 1.09$ and $K_i = 0.38$.

4 Evaluation of the wind turbine problematic mode shapes

Although the result shown in Figure 3 seems to be satisfactory, it was obtained considering the wind turbine as a perfectly rigid structure. To evaluate the real performance, the flexible mode shapes (and corresponding degrees of freedom) need to be enabled during simulation. In order to identify which are the problematic mode shapes, the DOFs must be progressively enabled.

The first DOFs to be simulated are the flaps DOFs of the blades. These are connected to the bending of the blade in a direction perpendicular to the plane of rotation. The modeling considers two mode shapes, the first flap mode and the second flap mode, corresponding to two degrees of freedom. The simulation result is shown in Figure 4 and is still satisfactory.

The next step corresponds to the activation of the edge DOF of the blades. This DOF is connected to the bending of the blades in a direction parallel to the plane of rotation. It corresponds to one mode shape, the first edge mode. Simulation result is shown in Figure 5.

Simulation shows that the edge mode provokes an instability in the rotor speed. This occurs because the standard control presented in Section 3 does not take into account this mode shape and the coupled dynamics of the turbine. Actually, the standard control is based only on the rotor azimuth variation. However, this variation interacts and influences on the edge bending.

To identify other possible problematic mode shapes, simulations are proceeded with all other

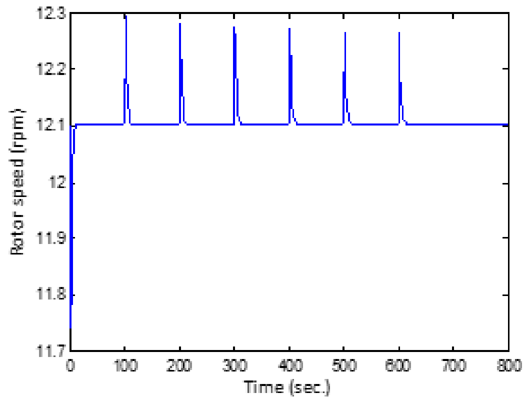

Figure 4: Rotor speed control, 3-DOFs enabled.

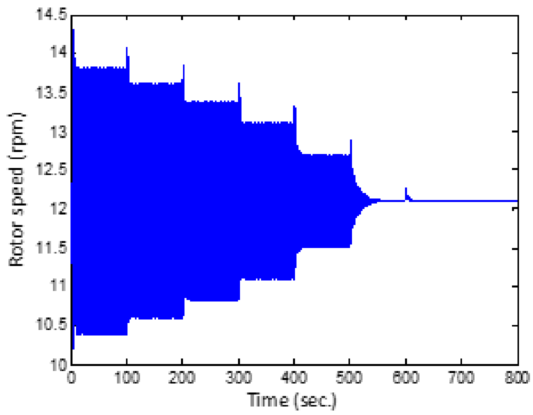

Figure 5: Rotor speed control, 4-DOFs enabled

DOFs (see Table 1) successively enabled in FAST. Due to space constraints, only the last simulation with all the DOFs enabled is presented in Figure 6.

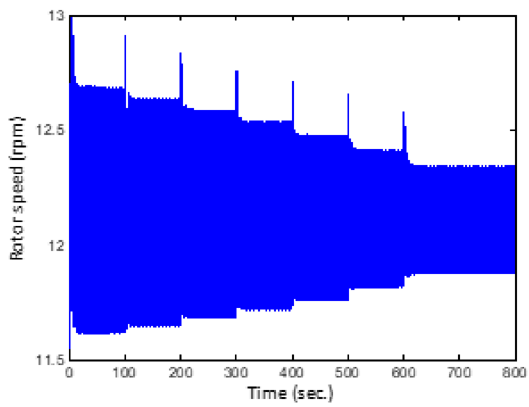

Figure 6: Rotor speed control, all DOFs enabled.

The conclusion was that only the edge mode shape was responsible for the undesired behavior.

5 Designing the state-space controller

The main goal is to design a new state space controller that controls the turbine rotor speed avoiding the undesired oscillations. In doing so two characteristics were taken into account:

- To use the less states variables possible while ensuring the desired behavior;
- The resulting system model must be controllable and observable.

The first one is concerned with the system model complexity while the second is concerned with the control realizability. The smaller system that achieve those characteristics was a 7-state model, considering the following DOFs and mode shapes:

- rotor azimuth DOF (1-state, velocity);
- drive-train mode shape (2-states, position and velocity);
- collective flap mode shape (2-states, position and velocity)
- collective edge mode (2-states, position and velocity).

The linearization is proceeded, obtaining a 7×7 state matrix with the following eigenvalues (poles):

$$eig(\mathbf{A}) = \begin{bmatrix} -1.54 + 22.5i \\ -1.54 - 22.5i \\ -1.21 + 10.7i \\ -1.21 - 10.7i \\ -2.51 + 3.9i \\ -2.51 - 3.9i \\ -0.49 \end{bmatrix} \quad (7)$$

Even when all poles are negative, i. e. it is a stable system, the desired behavior was not achieved. Such behavior was determined by the edge mode shape as previously stated and its corresponding pole must be determined. Running an eigenvector analysis was detected that $-1.54 \pm 22.5i$ correspond to the edge mode shape (position and velocity) which is also the less damped pole.

The solution to achieve the desired behavior is to increase the system damping coefficient, specially of the edge mode that is the cause of undesired oscillations. Since the primary objetive of the pitch control is the rotor speed, its mode shape need to be also identified. The real pole in -0.49 is easily identified as the correspondent of the rotor azimuth (velocity) since it is the only not complex solution.

Then the pole responsible for the edge mode will be placed at $-4.5 \pm 22.5i$ increasing the damping coefficient from 0.068 to 0.196. The pole responsible for the rotor azimuth mode will be placed at -2 in order to decrease the settling time, i. e. improve the system time response.

Using the pole placement technique, a gain vector $\mathbf{G}$ is determined to achieve the desired behavior. The system desired poles location are:

$$\mathbf{p} = \begin{bmatrix} -4.5 + 22.5i \\ -4.5 - 22.5i \\ -1.21 + 10.7i \\ -1.21 - 10.7i \\ -2.51 + 3.9i \\ -2.51 - 3.9i \\ -2 \end{bmatrix} \quad (8)$$

A new state space variable (wind speed disturbance) was included by using the Disturbance Accommodating Control (DAC) technique used in (Novaes Menezes, Araújo, Rohatgi and González del Foyo, 2018). Then using the Ackermann formula the gain for the feedback states was determined:

$$\mathbf{G} = [-5.98\ 0.022\ \ -0.10\ 1.43\ 0.19\ 0.006\ \ -0.025\ 0.01]$$

The simulation result for the rotor speed control is shown in Figure 7.

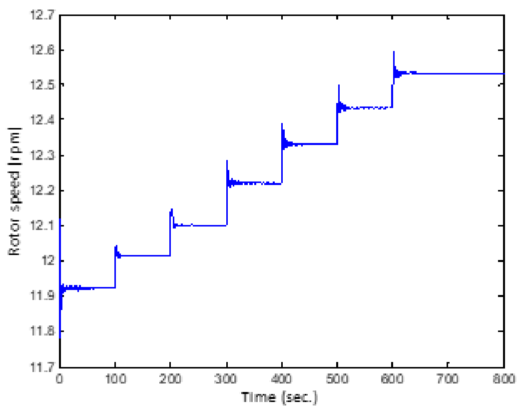

Figure 7: Rotor speed control, state-space controller, all DOFs enabled.

Even when the rotor speed was varied between 11.9 rpm to 12.6 rpm for a wind speed variation of 14 to 20 m/s there was not oscillations even when all available DOF where activated. The steady state error of ± 0.5 rpm was considered adequate in such scenario.

6 Conclusion

The state-space methodology can be used both for control and for modal shape dynamic analysis. In this paper, it has been proven the effectiveness of this method by identifying the mode shapes with the eigenvalues of the state matrix and, by consequence, with the poles of the transfer function matrix. By doing so, it is possible to develop an application of control-structure interaction, in which a control system can actively influence in the structure mode shapes, reducing or even eliminating the oscillations.

The approach here presented was applied on a large-scale wind turbine, with 5 MW of rated power and large rotor blades span. The problematic mode shape was identified as the edge mode shape, that caused the undesired oscillations. The corresponding eigenvalue was placed in a suitable location, increasing the damping in the mode and consequently improving the system response. The rotor speed remains controlled at 12.1 rpm incurring in a steady state error of ± 0.5 rpm that is considered adequate for the wind speed variation investigated. Using a try and error approach, a new pole location can be determined in order to improve the system behavior.

There was no additional problems detected, even with all the DOFs of the system enabled in simulation.

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