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Dynamic Design of an Electromechanical Pitching System for Wind Turbines by Means of Multi-Body Simulation

Fig. 1: Pitching system and blade

INTRODUCTION

The efficiency of wind turbines and their loads depend on wind speed, rotor rotation speed and pitch angle ß of the rotor blades. Since wind speed cannot be controlled wind turbine power and loads can be regulated by changing the pitch angle of the rotor blades or the rotational speed of the rotor. Most wind turbines use pitch angle control to change the forces on the rotor blade, regulate the power and perform maneuvers such as start-ups and shut-downs.

Many wind turbines are equipped with controlled electromechanical actuators to adjust the rotor blades. Taking the dynamic characteristics of the pitching system into consideration is crucial, e.g. for defining the control strategy and for the design of the pitch drive components.

In addition to determining the natural frequencies, the analysis of the system dynamics includes the simulation of transient load cases which represent critical cases of operation.

The main parameters characterizing the dynamics of the pitch process are the pitch rates and the interval between two sequential pitch processes. These parameters should not be selected solely on the basis of the desired power quality of the wind turbine, but must be adjusted to account for the dynamics of the wind turbine. Consideration of the natural frequencies of the tower, drivetrain, pitching system, and rotor blades are essential. Furthermore, the fluctuating loads on the rotor blade and their pitch drive must be taken into account. In order to achieve more accurate results in determining the natural frequencies of a pitching system, all mechanical components of the system, such as actuator, gear box and rotor blades,

> *"Taking the dynamic characteristics of the pitching system into consideration is crucial."*

must be modeled. The overall model of the pitching system used in time domain simulations may be divided into four subsystems between which interactions take place [8]. These subsystems are the mechanical, the aerodynamic, the electrical and the control subsystems.

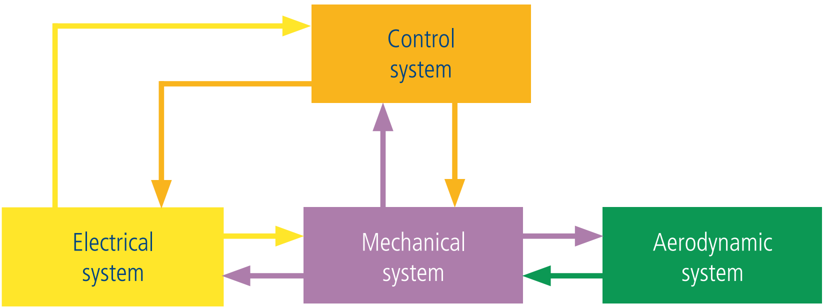

Fig. 2: Subsystems of the pitching system

MODELING OF THE PITCHING SYSTEM

The pitching system of a wind turbine can be divided into four subsystems (Fig. 2). The consideration of the interaction between these systems is essential in order to achieve a correct load calculation for the components of the total system [6].

MECHANICAL SUBSYSTEM

The mechanical subsystem includes all mechanical components of the pitching system: the rotor of the electric motor, the transmission elements (gearbox) and the rotor blade. This can be modeled as a multi-body system (MBS) with multiple degrees of freedom (cf. Fig. 3), which consists of rigid bodies which are connected to each other by massless spring elements. The modeling of the actuator and the transmission elements, such as the gearing, the shafts and the bearings, is based on the research report FVA-95 and further works [10, 7]. The rotor blade can be modeled as a bending oscillator. The parameters of the blade model are defined on the basis of the mass distribution and the bending stiffness distributions along the blade [1].

AERODYNAMIC SUBSYSTEM

The modeling of blade aerodynamics is based on elementary blade theory [3]. The influence of wind shear and the aeroelasticity of the rotor blade are also considered in the calculation model [6]. The rotor blade is divided into a number of blade elements for which the angle of attack α_A is calculated by iteration. The airfoil which is used provides the lift, drag and pitch moment coefficients c_L, c_D, c_M. After that the lift L and drag D forces, and the pitching moment M_{pitch} are determined using equations 1, 2 and 3 and Fig. 4:

- Equation 1:

$$L=\frac{\rho}{2}Ac^2c_L(\alpha_A)=\frac{\rho}{2}btc^2c_L(\alpha_A)$$

- Equation 2:

$$D=\frac{\rho}{2}Ac^2c_D(\alpha_A)=\frac{\rho}{2}btc^2c_D(\alpha_A)$$

- Equation 3:

$$M_{Pitch}=\frac{\rho}{2}c^2bt^2c_M(\alpha_A)$$

Where ρ is the air density (in kg/m³), A the surface of the blade segment (in m²), b the width of the blade segment (in m), t the chord (in m), Ω rotational speed of the wind turbine (in rad/s), r the local radius of the blade element, α_{Bau} is the twist angle of the blade segment, β is the pitch angle, U is the tangential velocity of the blade element (in m/s), V_2 is the wind velocity in the rotor plane (in m/s), c is the relative velocity at the blade segment (in m/s). The influence of the blade vibration on the fluctuated aerodynamic loads is considered in the calculation's model as well.

> ***"The complexity of the mechanical model affects the calculated eigenfrequencies."***

ELECTRICAL SUBSYSTEM

This system represents the behavior of the electric motor. There are many possibilities to model the electric motor which are different in their complexity and accuracy. The detailed method depends on the type of the motor used. If an asynchronous motor is used as an actuator, then its electromechanical behavior can be modeled on the basis of the space vector theory [9]. For other motor types, the modeling is based on the associated characterized equations [9]. In order to simplify the representation of the electric motor, the mechanical

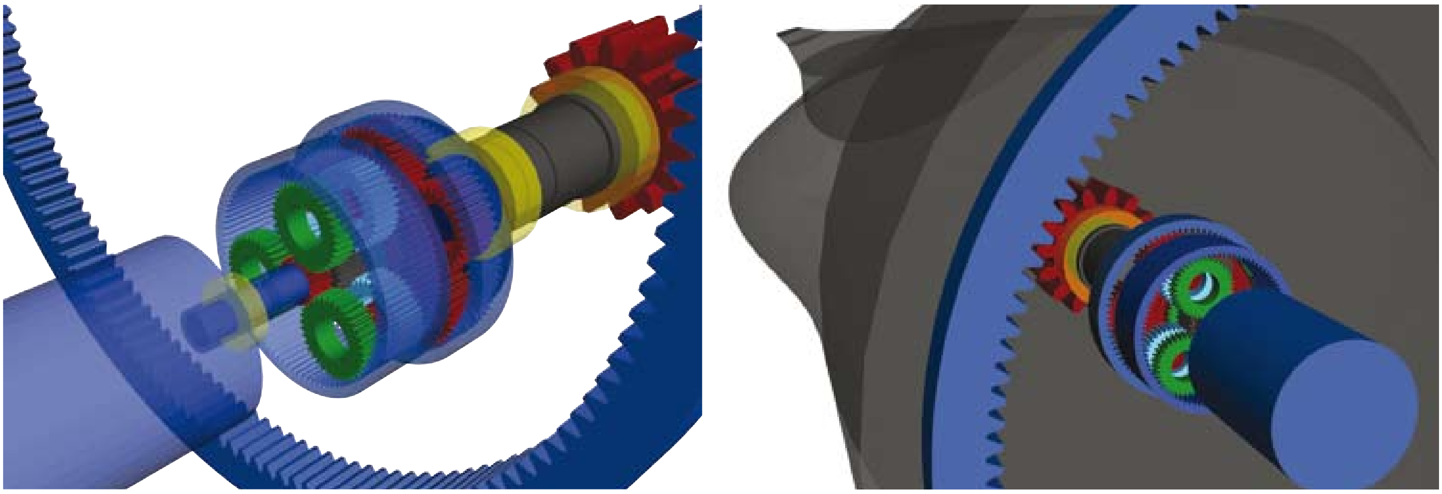

Fig. 3: SIMPACK model of the pitching system

characteristic curve in combination with the delay time, which is taken from the motor to develop the torque, are used.

CONTROL SUBSYSTEM

Fig. 5 shows the control loop of a pitch regulated wind turbine where the index *M* stands for the measured values and the index *S* for the demand (set-point). The control system consists of the following control loops [4], [2], [1], [6]:

- Pitch angle control loop
- Pitch rate control loop
- Motor current control loop

The controllers of these loops are modeled as PI controllers which are used to calculate the output (pitch angle, pitch rate or motors current demand) from the input (control error between the demand and the measured values).

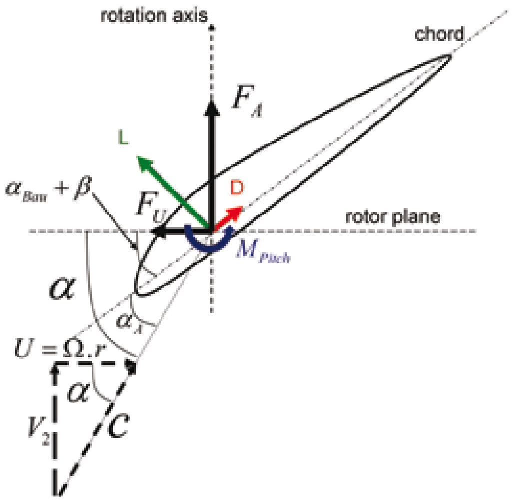

Fig. 4: Blade element velocities and forces

ANALYSIS IN THE FREQUENCY DOMAIN

The complexity of the mechanical model affects the calculated eigenfrequencies. Including the rotor blade in the pitching system model is necessary to achieve exact results. As the bending oscillations of the blade change the wind velocity along the blade, the blade loads fluctuate and lead to oscillating friction in the pitch bearing, causing fluctuated torsional loads in the pitch actuator. Thus, the blade bending vibrations are coupled with torsional vibrations in the pitch actuator (gear motor). Furthermore, the blade torsional properties affect the torsional frequencies of the total pitching system. Both the rotational inertia and the rotational stiffness are relevant. The connection between the blade wall and the pitch bearing inner ring is modeled as a force element. The rotational stiffness of this force element is calculated on the basis of measured blades torsional frequency using equation 4:

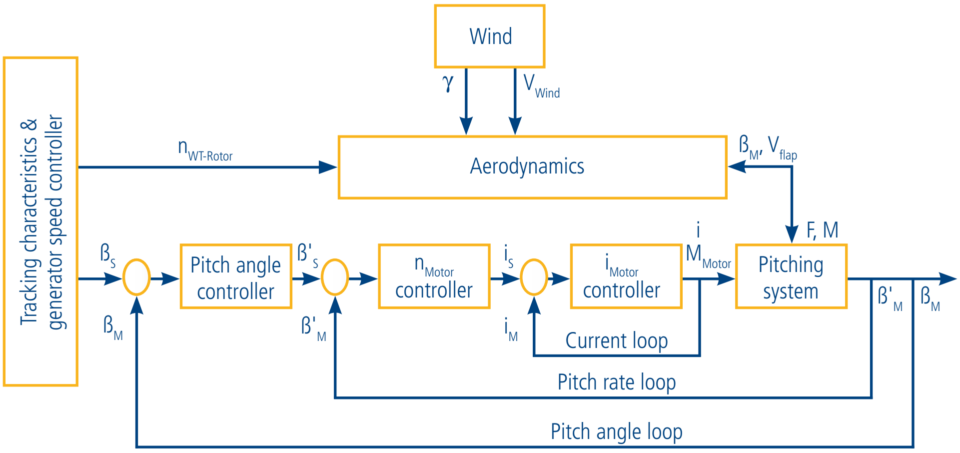

Fig. 5: Control loop of the pitching system

- Equation 4:

$$f = \omega/2\pi = \sqrt{K/J_P}/2\pi$$

This value is then varied in order to analyze the influence of the blade's rotational stiffness on the torsional frequencies of the pitching system. The calculated blade torsional stiffness (model C) was increased by a factor of ten in model D and reduced ten times in model E.
As table 1 shows, the torsional frequencies of the pitching system will change according to the blade rotational stiffness. This can lead to a critical state in the pitching system, e.g. when the system has an eigenfrequency close to the operating speed of the electric motor [6]. In addition, there are other influences of the blade torsional properties. The torsional oscillations of the rotor blade change the angle of attack along the blade [5]. This can lead to direct influences on the aerodynamic loads and on the stresses in the pitching system components [8].
After determining the pitching system's eigenfrequencies, the excitability of the

Model	C	D	E
Blade bending	0.75	0.75	0.75
	1.31	1.31	1.31
	2.45	2.45	2.45
	4.62	4.62	4.62
Blade torsional	15.06	29.46	5.16
Gear motor	108.50	175.40	100.12
& rotor blade	1147.60	1147.60	1147.60

Table 1: Calculated eigenfrequencies in (Hz)

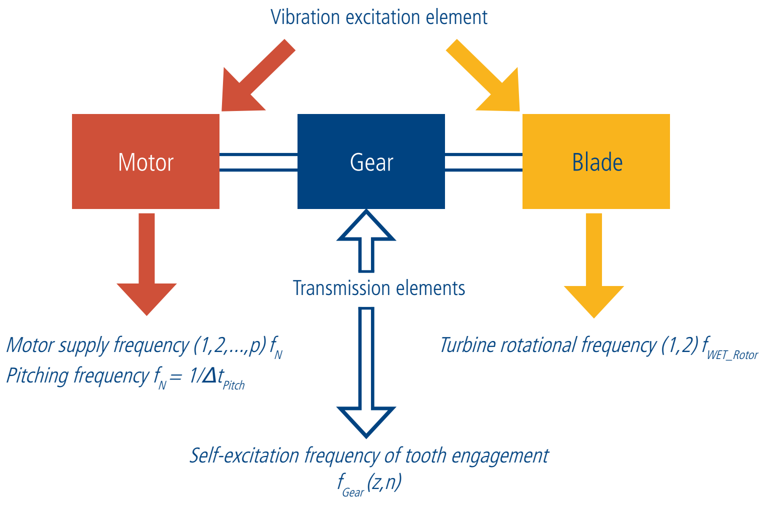

Fig. 6: Exitation frequencies of a pitching system

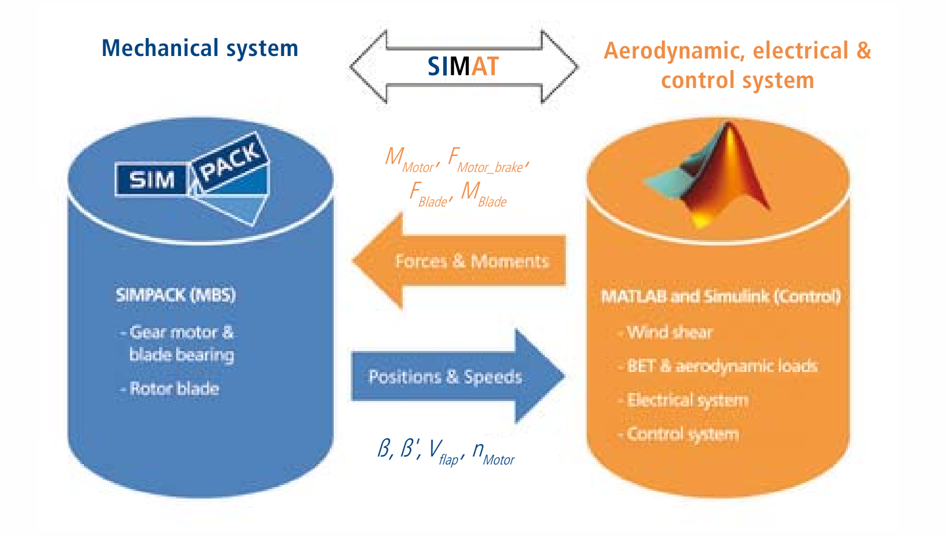

Fig. 7: Co-simulation of SIMPACK with MATLAB® and Simulink®

system's frequencies have to be analyzed. The excitation frequencies are related to the rotational speed of the wind turbine, pitch rate and pitch time interval, which are taken between two sequential pitch processes. In addition to these excitations, there will be a self-excitation with the tooth engagement frequency (Fig. 6) [6, 8].

> **"The achieved results could be used to design the components of the pitching system."**

ANALYSIS IN THE TIME DOMAIN

In addition to calculations in the frequency domain to determine the eigenfrequencies and the possible resonances of the pitching system, a co-simulation was carried out in the time domain in order to analyze the interaction between the different subsystems (Fig. 6). Many load cases were simulated, such as the pitching processes at start-up, power regulation (Fig. 8), and emergency stop of the wind turbine.

The results achieved could be used to design the components of the pitching system. Moreover, it is possible to use this model in the optimization of the dynamic behavior and the control system of the wind turbine.

DISCUSSION

Due to interactions between the aerodynamics, the mechanical subsystem and the electrical system, all these subsystems must be taken into account when analyzing the dynamic behavior of a wind turbine pitching system. The closed connection between the dynamics of the rotor blade and the pitch actuator dynamics requires a certain complexity of the mechanical model. By means of the presented modeling method, a correct load calculation of the overall pitching system can be carried out. Additionally, it is possible to test new developments of the pitching system and optimize the control behavior of the wind turbine.

In the simulation process, no data about the motor type and its inverter were available. The electrical system behavior was modeled with a delay element. A detailed modeling of the drive motor will be required for designing an effective pitch rate controller.

The presented simulation model can be used to determine the loads of the wind turbine drive train during the pitching process of the rotor blade. It was also efficiently used for testing new control strategies of wind turbines, e.g. the active damping of drive train vibrations via pitching processes.

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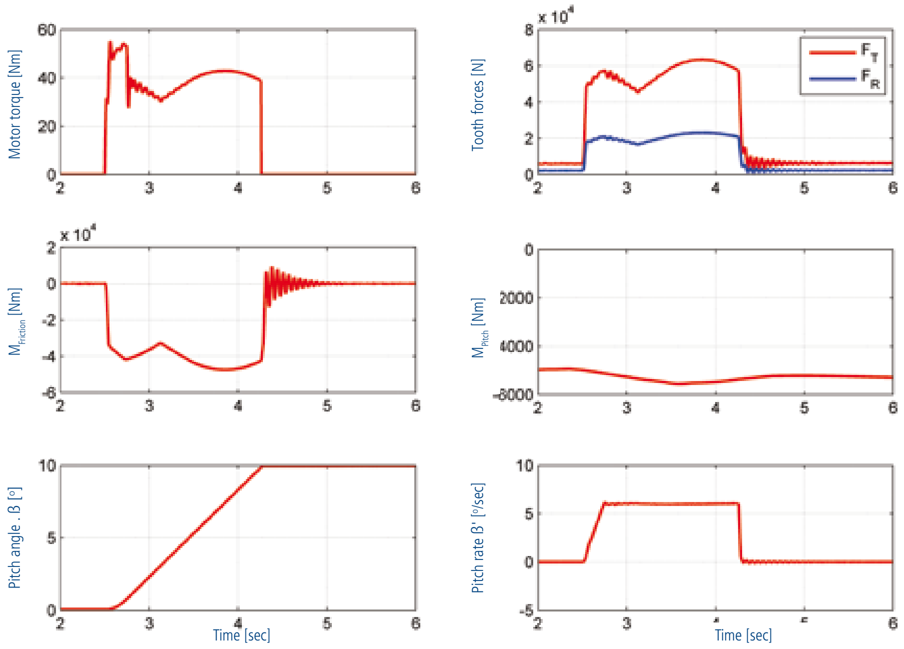

Fig. 8: Some results of a simulated pitching process $ß=0^o$->10^o, wind speed increases V_w=12->15