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"Integrated Wind Turbine Design"

1st order evaluation of smart blade-hub connection

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Contents

1. Problem statement

The overall scope of the task is to develop prototypes of semi-active devices as well as control strategies required to control the dynamic characteristics of the aerodynamic loads transmitted from the blades to the tower. The emphasis is on the extreme loading events i.e. strong wind gusts. In the first period of the project duration two concepts of adaptation were developed, one focusing on the bending stiffness adaptation and the second focusing on the torsional stiffness adaptation. For the first one a simple demonstrator has been built in order to show the general idea for the adaptive connection. The second concept, based on torsional stiffness adaptation has been invastigated in more detail. An aeroelastic model of a wind turbine has been built on which the stiffness control as well as complete release of the rotation about the blade axis was tested numerically. Results, as referred to a typical pitch control mechanism indicate substantial response time reduction and aerodynamic forces alleviation.

2. Adaptation of bending stiffness

2.1 The concept

The wind turbine operation under the extreme loading condition is in its limit state as far as the structural response is considered. The most severly stressed element is the blade root under the bending moment. Thus the first concept was to alleviate directly the bending stress in the root instead of mitigation of earodynamic forces. The blade – hub connection would be equipped with a controllable device with elastic and damping elements as shown on Fig. 1. During normal operation active elements would be stiff, whereas under an extreme gust their stiffness would be decreased for a short period of time. With the gust decay the stiffness would be brought back to the initial state.

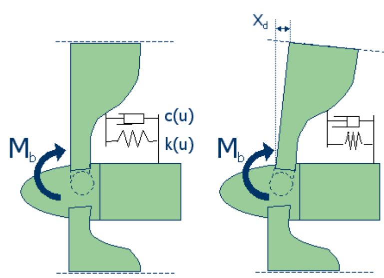


Figure 1: ***Bending stiffness adaptation concept***

2.2 Demonstration experimental set-up

A simple experimental set up was built as a demonstrator. The goal was to show - on a small scale, using a pneumatic device - the idea of adaptation of root characteristics and its impact on the response. System shown on Fig. 2 was manufactured and numerical simulation was carried out. Air outlet from the cylinder was connected to on/off valve. Control of the valve opening was obtained by means of a piezo actuator. Its integral part is mechanical amplifier of displacements which enables to obtain displacement of 0.2 mm. The response time of such piezo actuated valve is less than 1 ms. The blocking force of the actuator is enough to withstand forces of magnitude considered in the numerical simulations. In order to overcome the problem of too slow rate of flow back into the cylinder system was additionally equipped with air reservoir connected with the cylinder outlet. During the rising phase of load air from cylinder is controllably pressed to the accumulator and returned into the cylinder during the decay phase of loading. This forms a closed system which can work in a sequence. The feed-back was designed between the pressure transducer monitoring the pressure/force in the cylinder and the piezo actuator opening/closing the orifice. The results of both the simulations and the experiment are shown on Fig. 3. The results indicate 35% reduction in the reaction force of the pneumatic element. More details on simulations, the experimental set-up and the results can be found in [1].

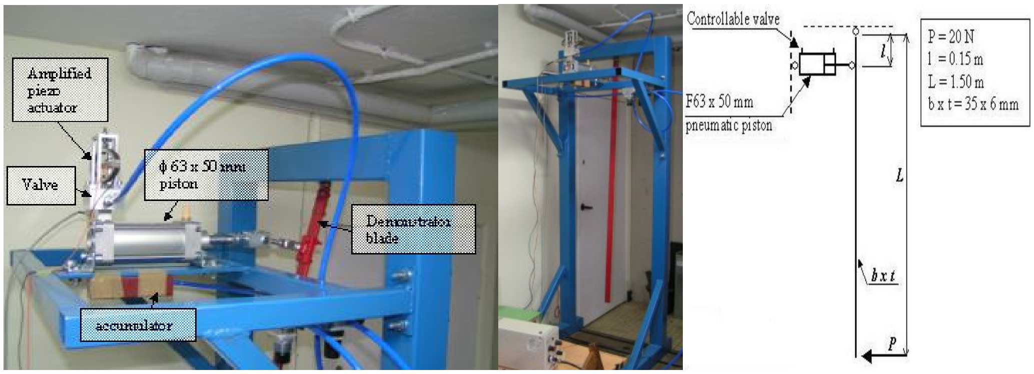


Figure 2: ***Experimental demonstrator built to show the adaptation concept***

This demonstrator was a starting point for the discussion about the adaptation concept and the technique which would be most effective in order to achieve fast aerodynamic load/stress alleviation in the wind turbine blade-hub interface. The torsional stiffness adaptation concept was then developed and investigated in more detail.

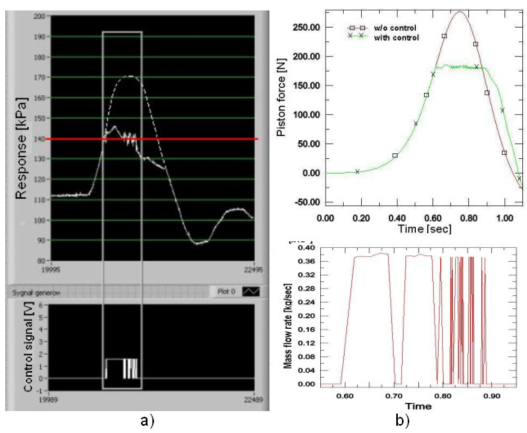


Figure 3: ***Mitigation of the response a) experimental; b) numerical***

3. Adaptation of torsional stiffness

3.1 The concept

During operation a wind turbine blade profile is pitched in order to obtain a desired angle of attack. As a result it is twisted and a torsional moment is applied at the root. A device that, under critical loading conditions, would reduce the torsional stiffness at the root, or allow a free rotation of the blade about the blade axis for a short instant of time could be an efficient and a very fast way to reduce the aerodynamic forces applied to the profile. In fact, such an action would allow the profile to turn to feather and thus to reduce the aerodynamic loading (cf Fig.4). Free rotation of the profile towards feather would be an inertial effect of such a modified structure, meaning that the device would be practically semi-active.
In further sections a numerical model of a wind turbine is described which was built in order to verify the effectiveness of the torsional stiffness adaptation. The bending moments in the connection were investigated as compared with a gust response without control (except for the

pitch control). The response time for the system was compared with a typical rate of blade pitching.

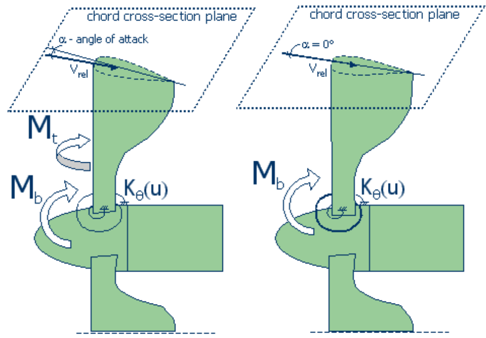


Figure 4: ***Torsional stiffness adaptation concept***

3.2 Assumed wind turbine model

A common methodology for many applications in a wind turbine control design is to test the new strategy on a simple aeroelastic model linearized around a typical opearation point. This provides a fair estimate of the overall system performance and enables to use a linear control theory. Then, for fine tuning of the system a complex fluid dynamics model can be elaborated.
The model used for simulations was built from scratch, since the commercial codes do not offer a run-time possibility to control the stiffness parameters of the structure. The model consists of two parts :

- Structural part, which consists of 12 dof listed in Table 1 (cf Fig. 5)
- Aeroelastic part which is built basing on the Blade Element Momentum Theory

3.2.1 Structural model

Table 1 and Figure 5 indicate the degrees of freedom of the structural model. Each blade is considered non-deformable and is represented by its three rotations. Bending, torsional and edge-wise stiffnesses account for the total blade deformations. All geometrical and stiffness data were taken from the UpWind Reference Wind Turbine downloaded from the UpWind website.
The model allows both for the pitch control as well as real – time stiffness modification according to any control law.

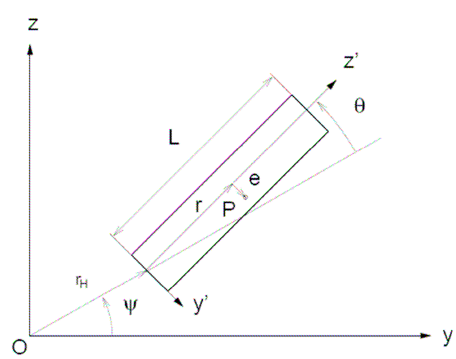


Figure 5: ***Structural model coordinates***

dof	name	description
1	X_t (t)	tower displacement along x axis
2	ψ (t)	rotor rotation about x axis
3	γ (t)	generator rotation about x axis
4	$\theta 1$ (t)	1st blade rotation about x' axis (edge-wise)
5	$\alpha 1$ (t)	1st blade rotation about z' axis (torsion)
6	$\beta 1$ (t)	1st blade rotation about y' axis (flap)
7	$\theta 2$ (t)	2nd blade rotation about x' axis (edge-wise)
8	$\alpha 2$ (t)	2nd blade rotation about z' axis (torsion)
9	$\beta 2$ (t)	2nd blade rotation about y' axis (flap)
10	$\theta 3$ (t)	3rd blade rotation about x' axis (edge-wise)
11	$\alpha 3$ (t)	3rd blade rotation about z' axis (torsion)
12	$\beta 3$ (t)	3rd blade rotation about y' axis (flap)

Table 1: ***Assumed degrees of freedom***

3.2.2 Aeroelastic model

The aerodynamic forces at each integration step were calculated on the ground of Blade Element Momentum Theory which is a standard tool for many initial studies in wind turbine development. Each blade was modelled in sections which conform with the profile data of the UpWind Reference Wind Turbine.

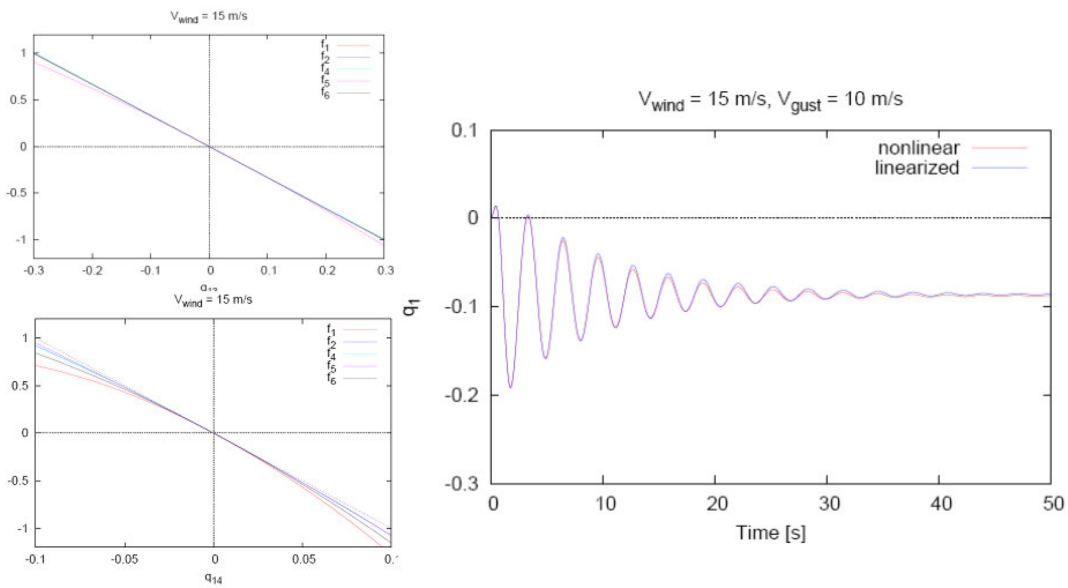
3.3 Verification of the aeroelastic model

The elaborated model was first submitted to the eigenfrequency extracion procedure. Obtained results were compared with the values calculated by ECN and with the UpWind Reference Wind Turbine. This is summarized in Table 2.

Mode	12 dof model [Hz]	BLADMODE 0 rpm [Hz]	Difference [%]
Tower	0,3165	0,3176	0,35
Reaction-less 1st flap	0,6386	0,6386	0,00
Collective 1st flap	0,6714	0,6576	2,10
Reaction-less 1st edge	1,0885	1,0885	0,00
Collective 1st edge	1,8008	1,7266	4,30
Reaction-less torsion	5,3267	5,3267	0,00
Collective torsion	5,3312	5,3219	0,17

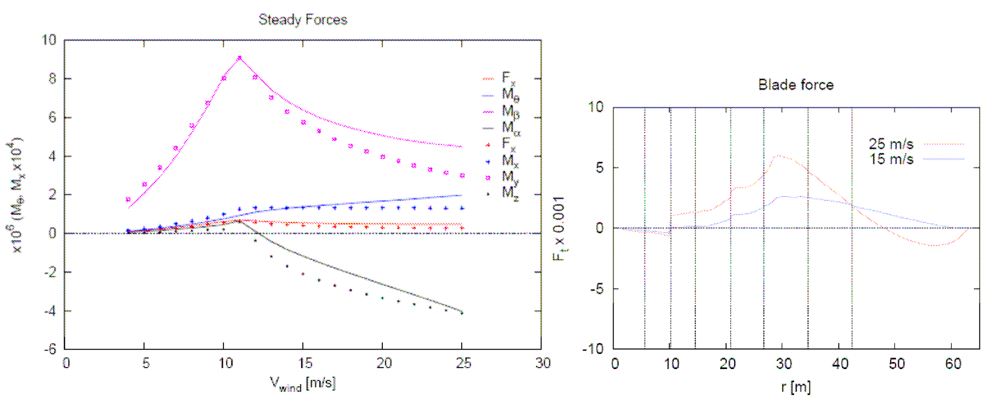
Table 2: ***Eigen frequencies comparison***

In the following step the model was excited with uniform wind field perpendicular to the rotor plane and a step ‘gust’ also perpendicular to the rotor plane. The calculations were carried out twice, i.e. for non-linear and linerised equations. A typical answer, as shown for the tower displacement on Firure 6b) indicate that the linearization of the equations of motion is a good estimate of the system answer. The aerodynamic forces were then linearised about the operating point, i.e. the steady state answer which led to the conclusion that, in some reasonable neighborhood, the aerodynamic forces can be estimated as linear functions of the generalized coordinates (cf Fig 6a). Finally calculated aerodynamic forces were compared with those obtained by ECN using a much more sophisticated technique, and a fair complience was obtained (cf Figure 7a).



a) b)

Figure 6: ***Linearization a) aerodynamic forces; b) equations of motion***



a) b)

Figure 7: ***a) aerodynamic forces compared with ECN results (dotted lines), changed angle of attack at 11m/s; b) resultant blade force along the blade radius***

3.4 Results

For the reference case the turbine at its operating state (wind speed 15 m/s) was submitted to the extreme operating gust acc. to the standard IEC 61400-1. For the adaptive case, during the wind gust rise the torsional stiffness at the root was reduced to zero, meaning that a free rotation about the blade axis was introduced (lines referenced ‘unclutched’ on the figures). The time interval for unclutching the blade was assumed 0.01s. The vertical line on the figures indicates the time instant of unclutching.
The goal of the simulations was to show how fast, if at all, the aerodynamic forces are reduced and how fast does the angle of attack turn to feather, as compared to a typical pitch mechanism rate. The process is semi-active which means that no additional actuator mechanism is assumed here and the blade rotation is an inertial process.
Obtained results show that a device which could free the blade rotation about the blade axis in case of an extreme wind gust is likely to both reduce the aerodynamic forces and turn the profile to feather much faster that any pitch control mechanisms.

The change of twist angle is shown on Figure 8. It takes approximately 1.5s to change the angle of attack by 1 radian, which gives the average rate of ca 38 deg/s. Pitch control mechanisms work at the typical rate of 6-7 deg/s. A substantial increase in the speed of angle of attack decrease could be helpful in particular during an emergency stop of a wind turbine.

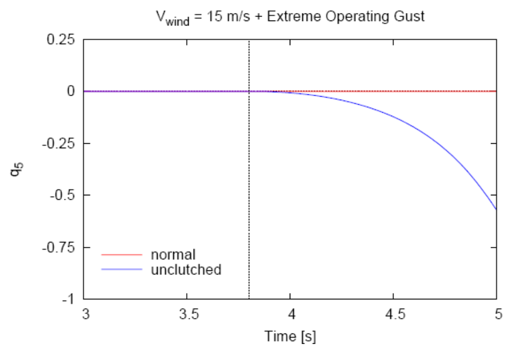


Figure 8: ***The blade twist angle in radians***

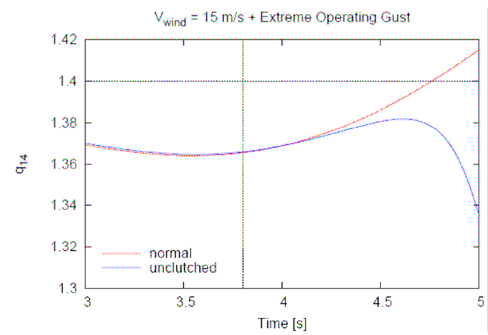


Figure 9: ***The rotational speed of the turbine in radians per second***

Figures 10 and 11 show that torque and bending moments values decrease rapidly. There is a potential of fast decreasing of bending moments applied at the root during an extreme wind gusts. The values of aerodynamic forces keep decreasing after changing the sign which is due to the fact that there was no 'clutching' back of the blades. The choice of the cluthing back time is crucial to the subsequent structural response and is currently under investigation.

Simulations with the reduced torsional stiffness by factor of 20 did not converge to a stady state response, but a classical flutter occured instead. In practice the stiffness will be reduced only for a relatively short period of time, which will not lead to flutter appearence. This proves however that the approach affects the flutter bahaviour and might be used to control the flutter in up-scaled turbines which tend to work closer and closer to the flutter regime.

The outcome of carried out so far simulations can be summarized as follows :

- Using semi-active technique the angle of attack could be theoretically decreased by ca 60 deg in 1.5s.
- Fast turn of the profile to feather could substantially reduce the loading of a turbine, in particular the bending moment at the root despite the rising of an extreme wind gust.
- 'clutching' the blade back in order to return to initial stiffness is under development
- numerical tests of the approach aiming at controlling the flutter should be carried out.

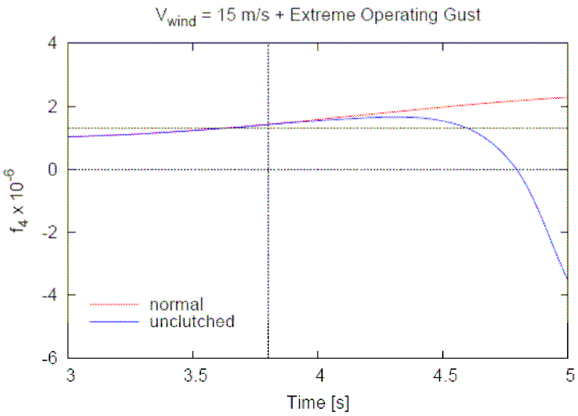


Figure 10: ***The torque [Nm]***

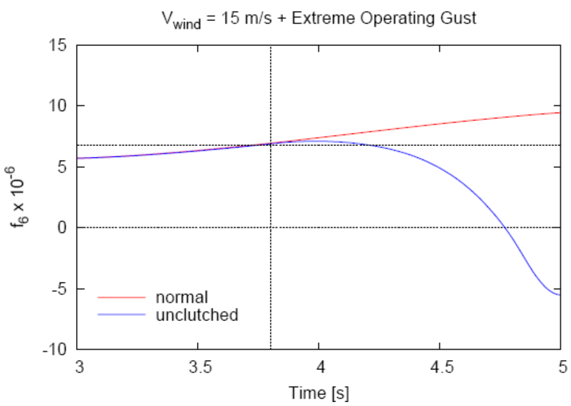


Figure 11: ***The bending moment at blade root [Nm]***

4. Practical implementation – the outlook

- ## MR clutch integrated with the pitch control mechanism

A clutch designed on top of the pitch control mechanism could realize the strategy of releasing the rotational degree of freedom of a blade under critical loading (cf Fig 12). Its characteristics should be controllable by means of magneto-rheological fluid in order to smooth the transition process between 'clutched' and 'unclutched' states.

- ## Lab-scale MR clutch verification

First step to implement such a device is to test the possibilities of application of MR fluid based clutch in a wind tunnel. For this puprose an experimental clutch is under development which will be first used in a lab to control the torsion of the shafts as shown on Figure 12.

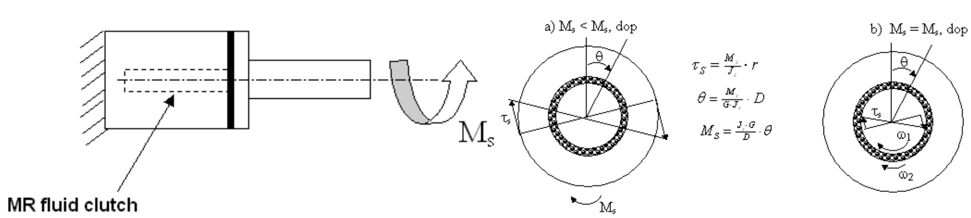


Figure 12: ***MR-based torsional clutch***

- **Low-speed wind tunnel experiment – planned**

In the next step the MR clutch will be used in a wind tunnel experiment to verify the reaction time of such a divece against the theoretical angle of attack rate obtained in the simulations.

Figure 13: ***Wind tunnel experiment with the torsional clutch***

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