Sliding mode control design and its application on floating wind turbine

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Supported by WEAMEC program

First objective: design of a new kind of controller for floating wind turbine in Region III

- Control objectives: regulation of power output at its rated value, and reduction of the pitch motion of the floating platform
- Robust control versus uncertainties and perturbations
- Very reduced information on the modeling
- Low tuning effort and low–computational capability
- High level performances (power, tower motion)

Second objective: evaluation of the performances of the proposed control strategy on an Experimental set-up and comparison with controllers (GSPI, LQR).

Modeling and control design based on linear control theory

- Linear dynamic model obtained from FAST
- Reduced state-space model: rotor velocity, platform pitch motion

$$x = \begin{bmatrix} \varphi & \dot{\varphi} & \Omega_r \end{bmatrix}^T \qquad u = \beta_{col}$$

Collective Blade Pitch Control

- Linear model around an operating point depending on wind conditions and rotor velocity

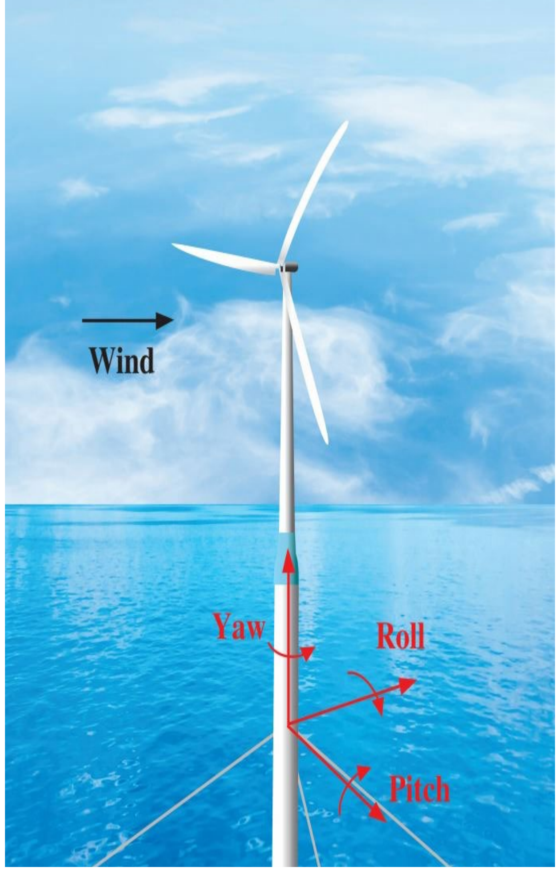
$$\boxed{\dot{x} = A_{Avg} \cdot x + B_{Avg} \cdot u + B_{d\,Avg} \cdot \delta}$$

Wind speed: 18 m/s
Rotor speed : 12.1 rpm

$$A_{Avg} = \begin{bmatrix} 0 & 1 & 0 \\ -0.0141 & -0.0405 & -0.0004 \\ -0.0757 & -2.3031 & -0.2304 \end{bmatrix}, B_{Avg} = \begin{bmatrix} 0 \\ -0.0035 \\ -1.1864 \end{bmatrix}, B_{d\,Avg} = \begin{bmatrix} 0 \\ 0.0001 \\ 0.0276 \end{bmatrix}$$

Wind speed: 20 m/s
Rotor speed : 12.1 rpm

$$A_{Avg} = \begin{bmatrix} 0 & 1 & 0 \\ -0.0141 & -0.0403 & -0.0006 \\ -0.0679 & -2.5069 & -0.3182 \end{bmatrix}, B_{Avg} = \begin{bmatrix} 0 \\ -0.0035 \\ -1.3856 \end{bmatrix}, B_{d\,Avg} = \begin{bmatrix} 0 \\ 0.0001 \\ 0.0030 \end{bmatrix}$$



Region III: from 11.3 m/s to 25 m/s

Drawbacks

- At each operating point corresponds such a system -> use of a large amount of systems for the whole operating domain
- Consequence: huge effort for control design - **1 operating point = 1 linear system = 1 controller tuning** (**some solutions:** GSPI [Jonkman *et al.*, 2009], LQR [Namik et al. 2008], …)

An other point-of-view [Cheng and Plestan, *Wind Energy*, 2021]

$$\dot{x} \quad = \quad A_{Avg}(x,t)\cdot x + B_{Avg}(x,t)\cdot u + B_{d_{Avg}}(x,t)\cdot\delta \quad \Rightarrow \quad \dot{x} \quad = \quad f_{wt}(x,t) + g_{wt}(x,t)u$$

Uncertain nonlinear system

Questions: how to design an efficient control strategy supposing that the dynamics of the system is not well-known, *i.e.* functions f_{wt} and g_{wt} are not known ? that the system is highly perturbed ?

To summarize

- The system on which the control design is made reads as

$$\boxed{\dot{x} \;=\; \boxed{f_{wt}(x,t)} + \boxed{g_{wt}(x,t)}u} \qquad x = \begin{bmatrix} \varphi & \dot{\varphi} & \Omega_r \end{bmatrix}^T \quad u = \beta_{col}$$

Unknown functions (supposed bounded, but unknown bounds)

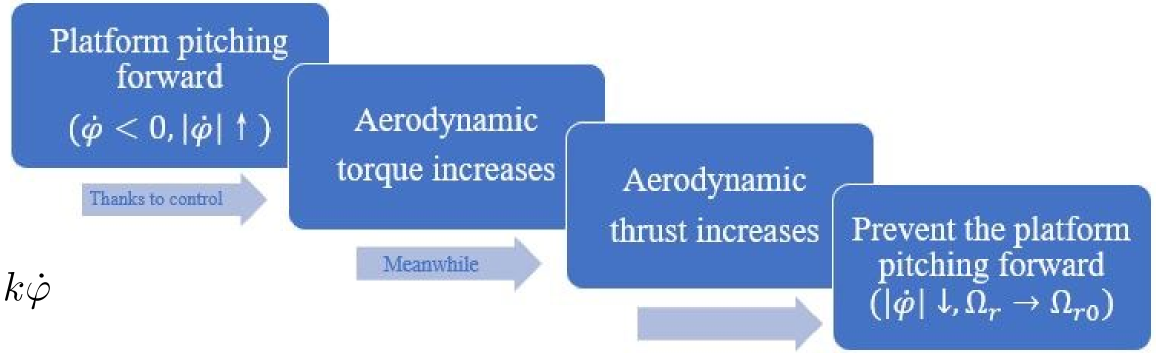
Collective Blade Pitch Control

- <u>Control objective</u>: power regulation to its rated value and limitation of tower pitching

Control output [Lackner, 2009; Lackner, 2013]

$$\boxed{S \;=\; \Omega_r - \Omega_{r0} + k\dot{\varphi}}$$

$$\Omega_r^* \;=\; \Omega_{r0} - k\dot{\varphi}$$



Assumption: rel.deg.(S)=1.

Question: how to define the control input u forcing S towards 0 ?

From **previous assumption**, dynamics of the output reads as

$$\dot{S} = \boxed{a(\cdot)} + \boxed{b(\cdot)} u$$

Unknown functions (supposed bounded, but unknown bounds)

A recent solution [Gutierrez *et al.*, 2021] named ***simplified adaptive supertwisting algorithm (SAST)***

- It forces S towards 0 in spite of perturbations and uncertainties
- It requires **no information on *a* and *b***
- It requires a very limited number of tuning parameters
- It requires low-computational capabilities

Sliding mode control theory

$$u = -2L|S|^{\frac{1}{2}}\mathrm{sign}(S) - \int_0^t \frac{L^2}{2}\mathrm{sign}(S)d\tau$$

Dynamic gain

$$\dot{L} = \begin{cases} L\left(|S| - \mu\right), & \text{if } L > L_m \\ L_m & \text{if } L \leq L_m \end{cases}$$

Only two parameters are required for the whole operating domain

- μ : accuracy
- L_m : minimal value

SAST

$$
\begin{aligned}
u &= -2L|S|^{\frac{1}{2}}\mathrm{sign}(S) - \int_0^t \frac{L^2}{2}\mathrm{sign}(S)d\tau \\
\dot{L} &= \begin{cases} L\left(|S| - \mu\right), & \text{if } L > L_m \\ L_m & \text{if } L \leq L_m \end{cases}
\end{aligned}
$$

Principle

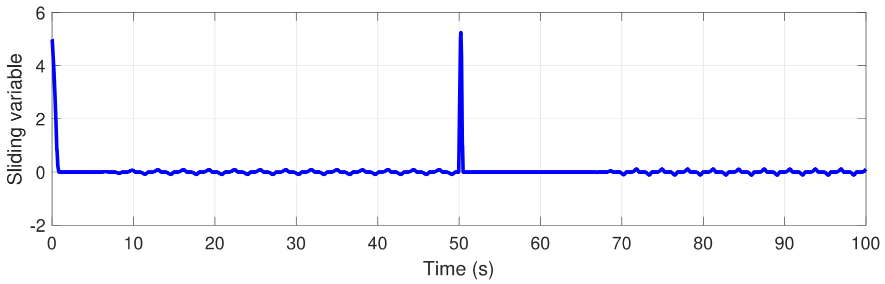
- The gain L must be large enough to ensure the convergence towards 0 but not too large to reduce the energy consumption and the control input oscillations.
- If abs(S) > μ (inaccuracy), the gain L increases - convergence towards to 0.
- If abs(S) < μ (accuracy), the gain L decreases – reduction of energy and oscillations.

Example

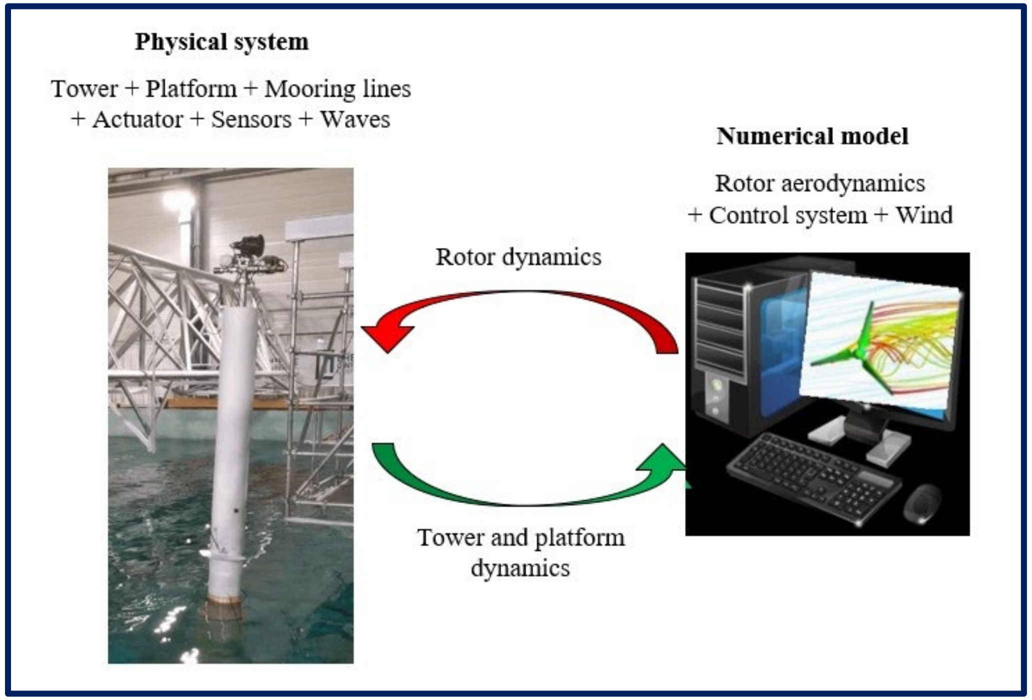
$$\boxed{\dot{S} = u + \varrho(t)}$$

$$\varrho(t) = \begin{cases} 10\sin(2t) & \text{if } t \leq 50 \ sec \\ 50\cos(2t) & \text{if } t > 50 \ sec \end{cases}$$

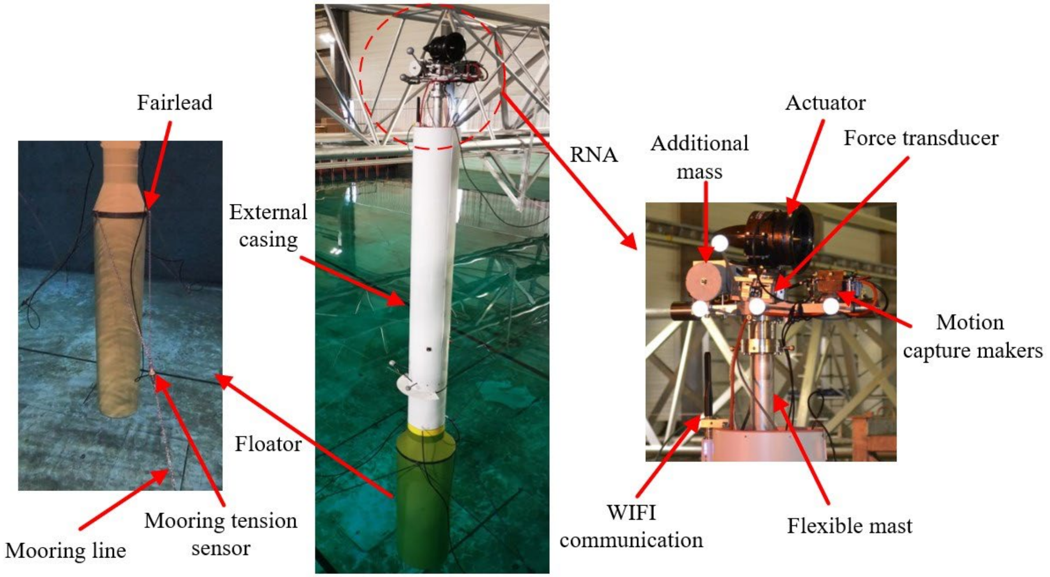
$$L_m = 0.005, \ \mu = 0.03$$



Experimental set-up [Arnal, Ph.D. thesis, 2020]



1:40 scale model based on DTU 10MW wind turbine (RNA and tower) and OC3 5 MW Hywind (spar-buoy floating structure)



The actuator allows to generate the aerodynamic forces calculated by the numerical simulations.

	Scale 1:40
RNA mass [kg]	12.45
Hub height above SWL [m]	3.03
Tower height [m]	2.666
Tower mass [kg]	13.48
Floater mass [kg]	303.8
Anchor depth [m]	5
Mooring line diameter [mm]	3.7
Fairleads depth [m]	-0.335

Comparison between

- the GSPI controller based on DTU approach [Hansen and Henriksen, 2013]

$$u = K_p e(t) + K_i \int_0^t e(\tau)\mathrm{d}\tau$$

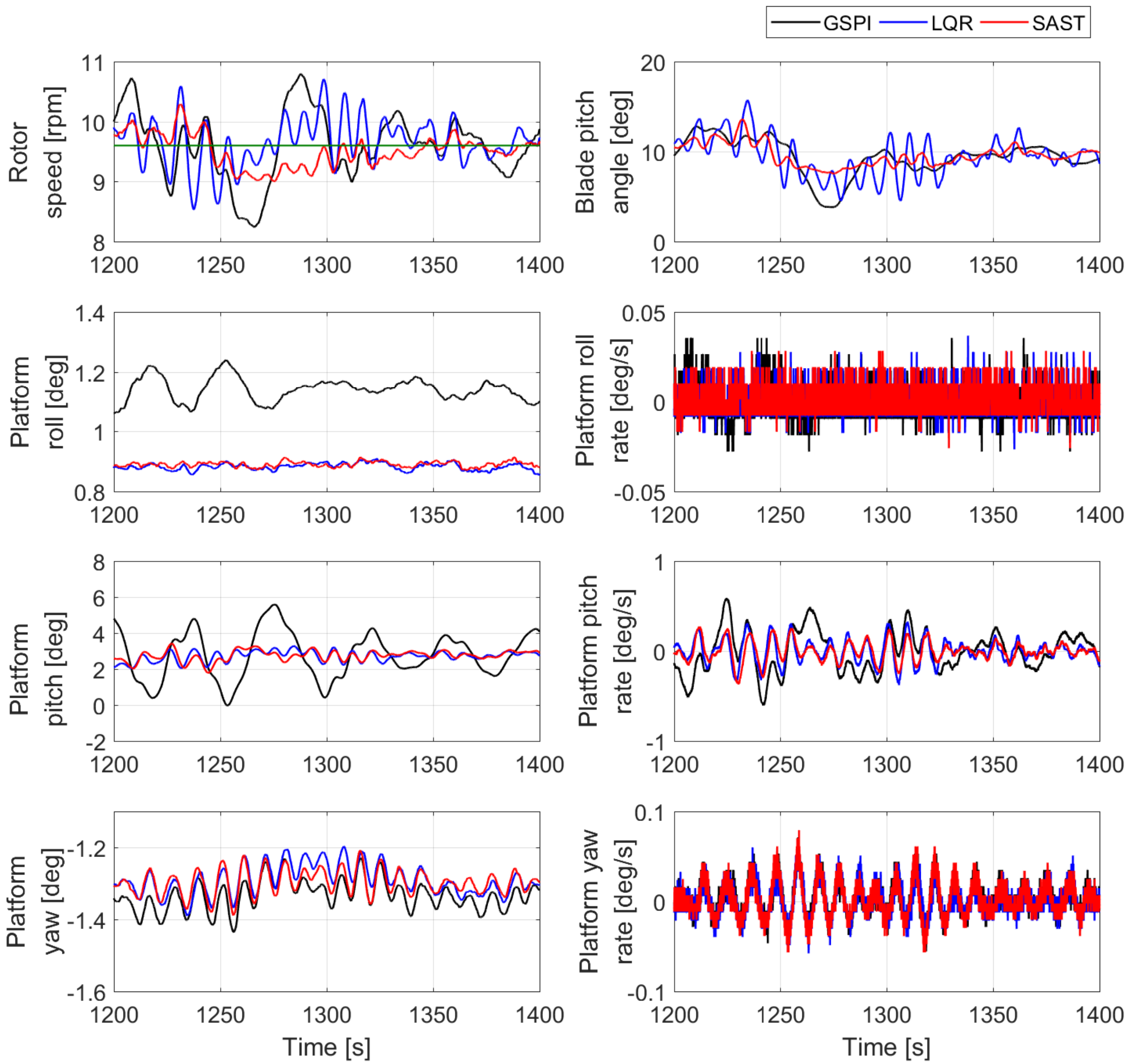
- the LQR controller developed by D ICE company (based on linear model)

$$u = -k_{LQR} \cdot x \qquad J = \lim_{t \to \infty} \int_0^T [x^T Q x + u^T R u] dt$$

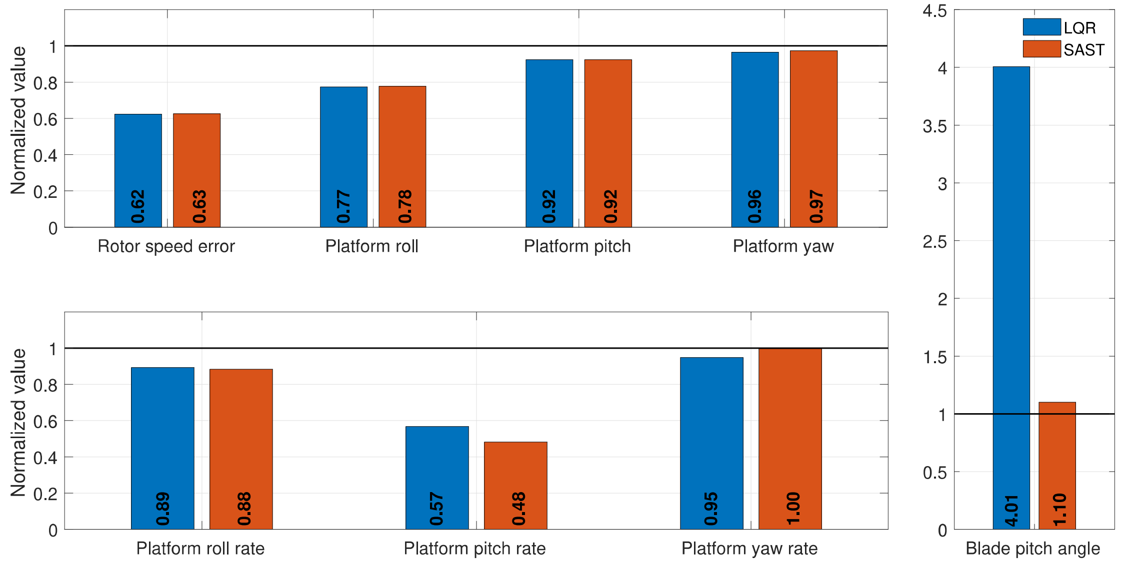
- the SAST control strategy (only two parameters)

Test conditions

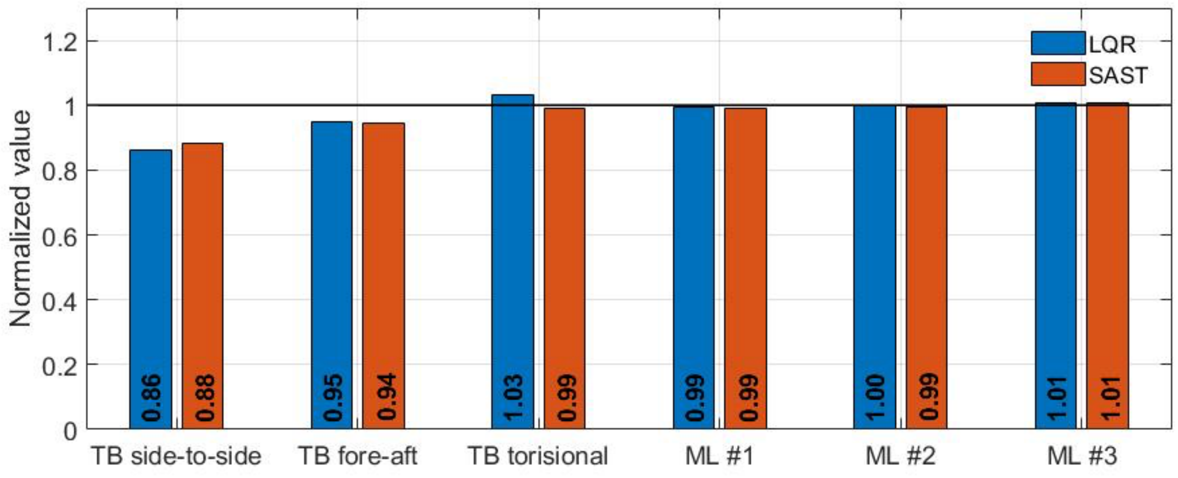
- 14 m/s stochastic wind with 9% turbulence intensity
- Irregular wave with significant height of 3 m, peak spectral period of 12 sec.



- Better tracking of rotor speed with LQR and SAST controllers
- Reduction of platform angles (roll, pitch)
- Reduction of pitch rate

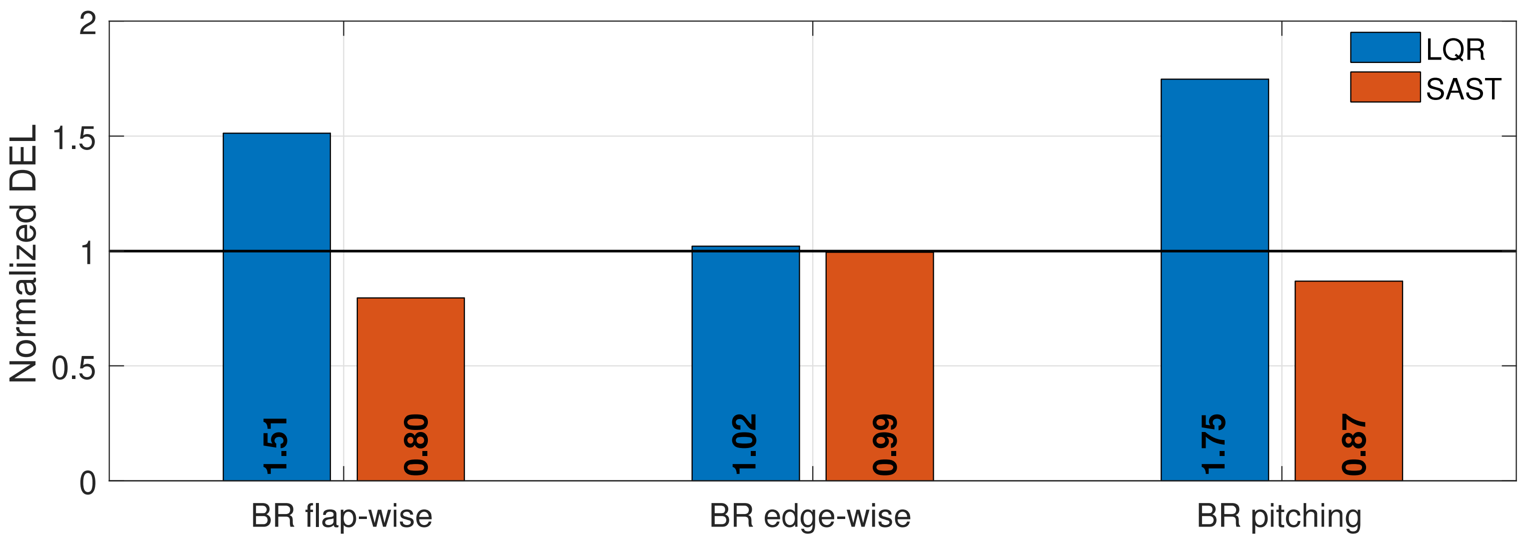


Normalized RMS/VAR values of performances indicators (Black line = 1: GSPI)



Normalized STD values of Tower Base moments and Mooring Lines tensions (Black line = 1: GSPI)

The system allows to get, by data replaying and simulations, unmeasured variables as blade roots (BR) moments



Conclusions (for these tests)

- SAST and LQR have reduced rotor speed error and platform pitch motion
- The blade pitch actuator is more solicited with SAST and LQR than GSPI
- The mechanical contraints (as mooring lines tension, blade roots moment) are reduced with SAST

Conclusions

- Proposition of a new control approach for floating wind turbines (collective blade pitch control)
  - Robust control, no modeling of the system is required
  - Reduced number of tuning parameters (only 2)
  - Low-computational capability requirement

- Validation of this approach on an experimental set-up
  - Improvement versus GSPI in terms of accuracy/tracking, without significative additional fatigue loads
  - More intensive use of the input acuator (blade pitch angle)

Other/Future works

- Evaluation of the proposed control strategies in numerous other kinds of scenarios
- Control design in the frame of Individual Blade Pitch (IBP) control [Cheng and Plestan, revision in *Ocean Eng.*, 2021]
- Introduction of electrical part of the system, and control design of the whole system [Cheng and Plestan, *Wind Energy*, 2021]
- Application to the control in Region II, and to control to the switching Region II-Region III.