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Wind Tunnel Testing on Negative-damped Responses of a 7MW Floating Offshore Wind Turbine

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Abstract

For pitch-controlled Floating Offshore Wind Turbines (FOWTs), the instability problem might occur by the coupling of the blade pitch control and the floater pitch motion, which leads to adverse effect on the loads on the FOWTs [1]. Some experiments of scaled tank tests for FOWTs have been performed[2][3]. However, there are few experimental studies where the unstable motion of FOWT due to the negative damping is realized with a tank or wind tunnel testing using a scaled FOWT model. In this paper, we proved experimentally the unstable motion of FOWT caused by the pitch control and validated an enhanced control method to suppress the negative damped response of the FOWT.

Objectives

- To realize the negative damping by wind tunnel testing
- To find out effects of control parameters for the rotor speed control on the stability of a FOWT
- To validate an enhanced control method to suppress the negative damped response of the platform.

Methods

1. Overview of wind tunnel testing

We performed a series of wind tunnel test campaign at the Mitsubishi Heavy Industries, Ltd. wind tunnel facility, using a 1/64 scale 7MW FOWT model equipped with the blade pitch actuator to control the rotational speed of the rotor during the full load operation. The floating platform used is categorized into the spar-buoy type. The wind tunnel is equipped with a small water tank, which enables wind and wave combined conditions.

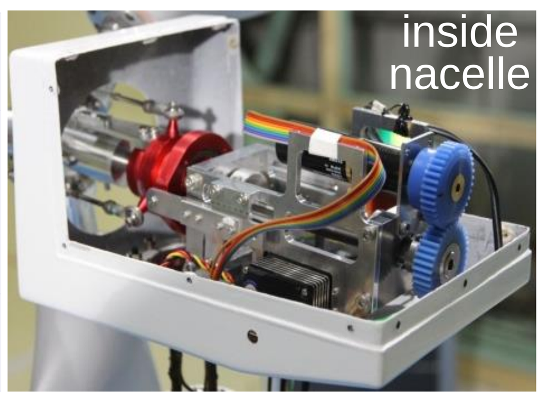
		Prototype	Wind tunnel model
Specification	Rated power	7,000 kW	3.3 W
	Rated rotational speed	10.3 rpm	82.4 rpm
	Rotor diameter	167 m	2.61 m
	Hub height	105.3 m	1.65 m
Controller		Variable-speed pitch regulated	
Fluid dynamic condition	Froude No.	equal	
	Reynolds No. (blade)	$5 – 9 \times 10^6$	$1 – 2 \times 10^4$

2. Aerodynamic problem due to Froude similitude

Froude and Reynolds scaling cannot be satisfied simultaneously[2]. When the Froude similarity rule is applied for this test, it causes an aerodynamic problem caused by the 1/512 scaled Reynolds number compared to the full scale turbine; this very low Reynolds number with the order of 10^4 results in definitely poor rotor performance and loads[2]. To ensure the similarity of the test model' s power and thrust with the real turbine, rotor blades were re-designed using thinner aerofoil and wider blades than the full scale prototype rotor.

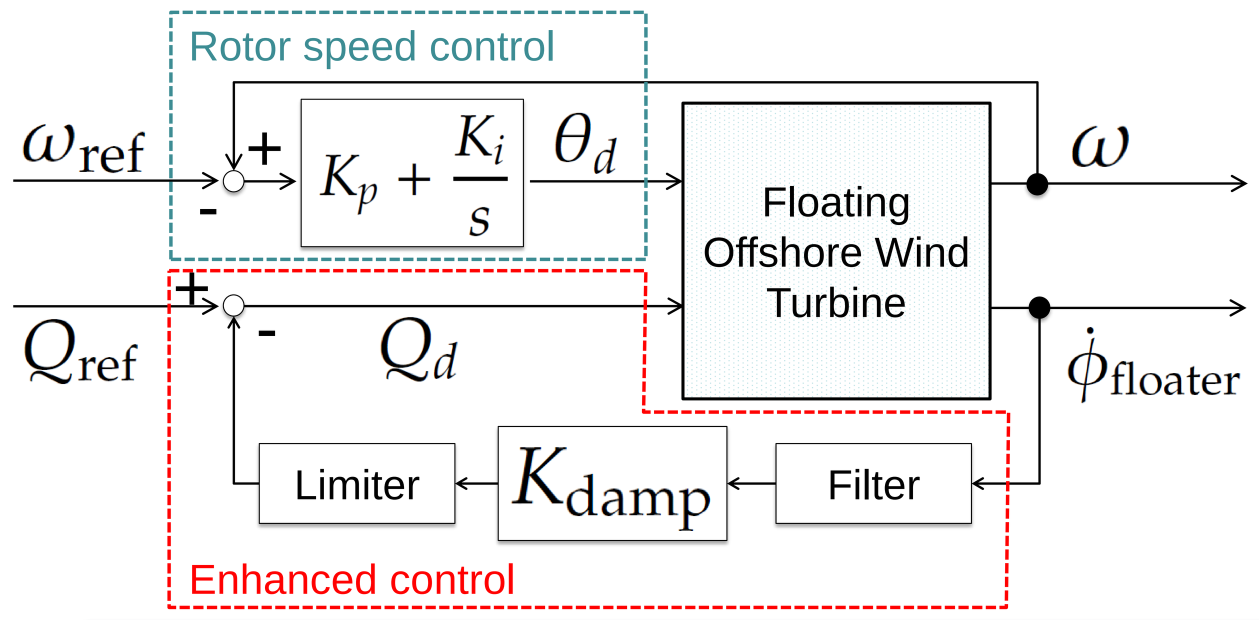
3. Features of the scaled model

Rotor blades	■ Re-designed for low Re no. ■ Lightweight carbon blades
Nacelle	■ Variable-speed pitch-regulated control ■ with a AC servo motor used as generator
Floater	■ Advanced-spar type designed by JMU[4]



4. Enhanced control to suppress the negative damping

Inspired by the NMPZ compensation method[5], the enhanced controller suppress the instable floater pitch motion by adding damping to the coupled system between the rotor speed control and the floater motion. This damping is provided by the feedback of the floater angular velocity to the generator torque demand. The design of the gain K_{damp}, filters and limiters are elaborately optimized to maximize the suppressing effect.



Experimental Results

1. Steady rotor performance and thrust

The re-designed rotor blades for the low Reynolds number and the pitch-regulated controller are verified in terms of:

- CPmax=0.32 and CT=0.88
- constant power above the rated wind speed of 1.5 m/s (=12 m/s in real scale)
- negative slope of thrust curve.

This negative thrust curve is essential to realize the negative damping.

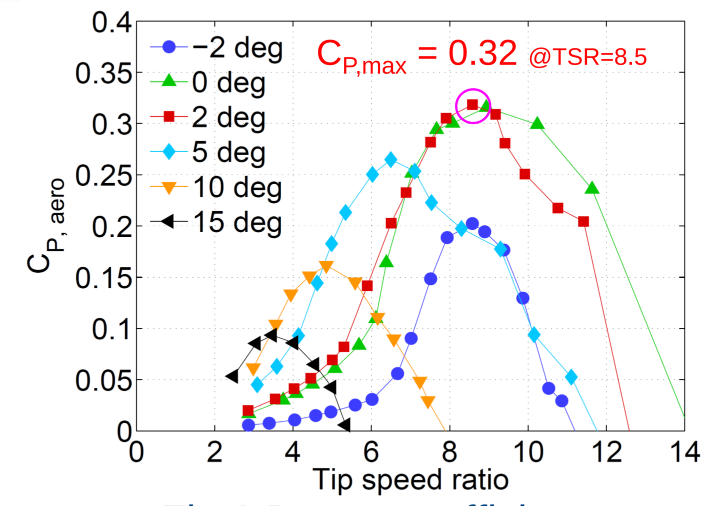


Fig.1 Power coefficient

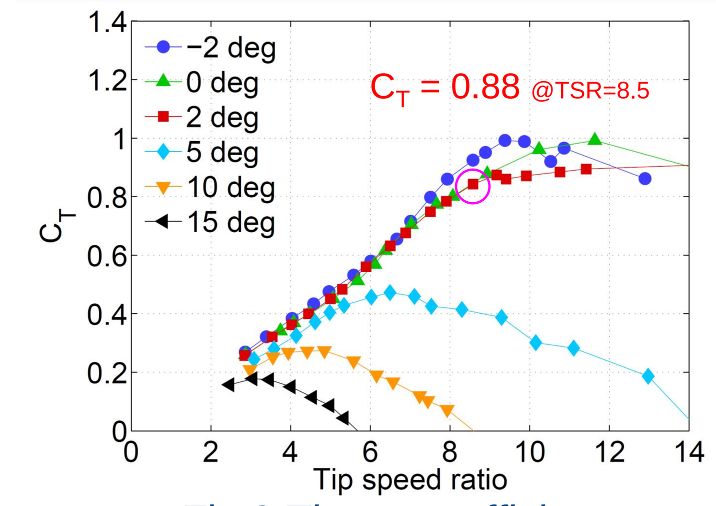


Fig.2 Thrust coefficient

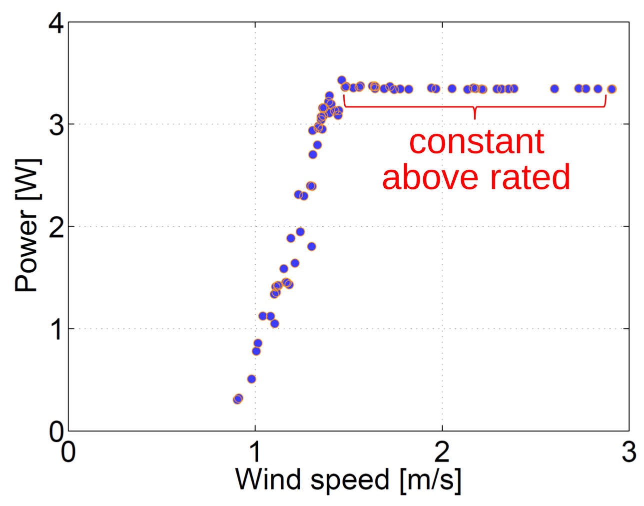


Fig.3 Power curve

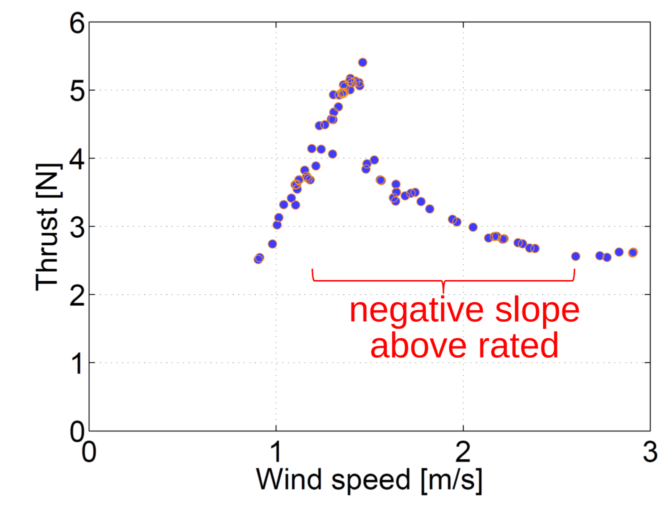


Fig.4 Thrust curve

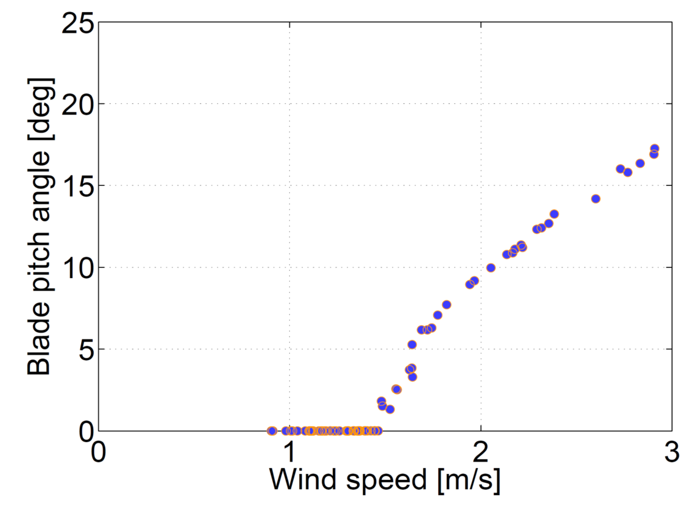


Fig.5 Pitch angle

2. Negative damping of FOWT

With steady wind speeds of 1.8-2.0 m/s (14-16 m/s for the real turbine) and no wave, the negative damping was captured. The rotor speed controller gains used are conventional settings for a bottom-fixed WT. The stop motions of the pitch oscillation show that: (1) the pitch of FOWT remained stationary at the measurement start; (2)(3)the FOWT began oscillation of pitch motion; (4)the amplitude of pitch motion was increasing with lapse of time and reached the limit cycle. The time series clarifies the negative damping (*Fig.7*).

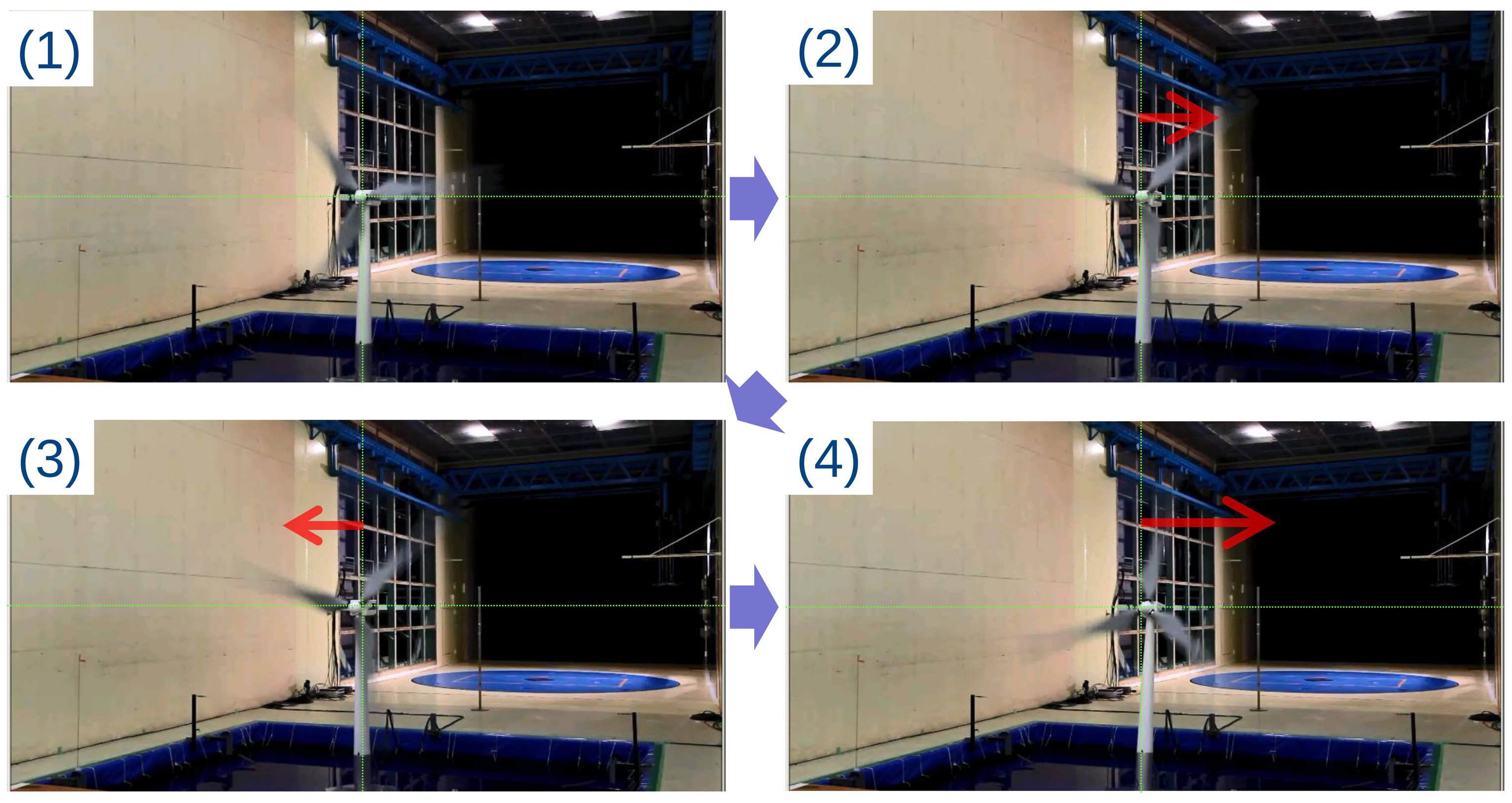


Fig.6 Stop motions of the negative damping

3. Bandwidth effect and validation of the enhanced controller

The values of logarithmic decrement were estimated from the pitch motion as index of the stability. Decreasing the rotor speed controller bandwidth to the natural period of floater has positive effect on the stability but it increases the rotor speed fluctuation. The enhanced controller to reduce the negative damping was validated.

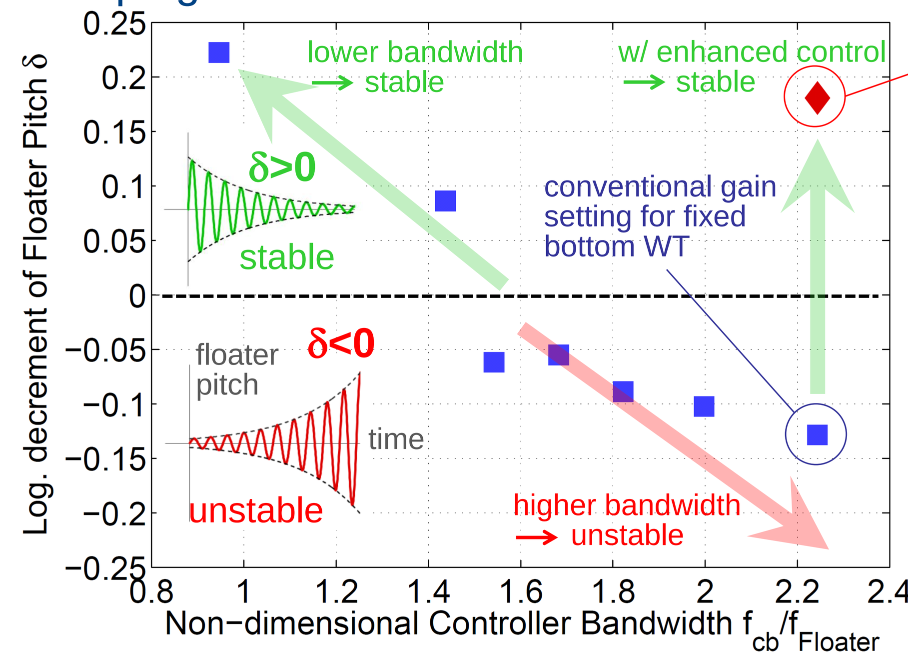


Fig.8 Effect of controller bandwidth on stability
x-axis: bandwidth of the rotor speed controller
y-axis: log. decrement estimated from measured floater pitch fluctuation

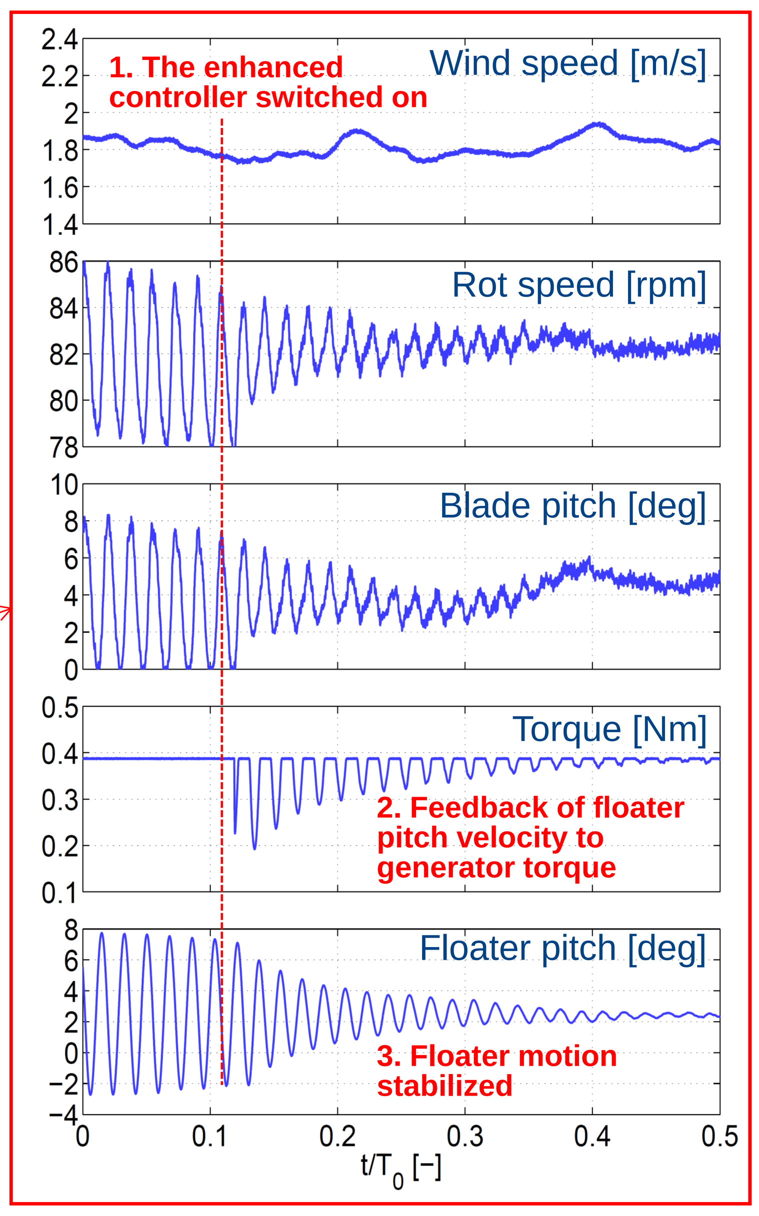


Fig.9 Effect of the enhanced controller
FOWT response with the enhanced controller added to the conventional speed controller gain

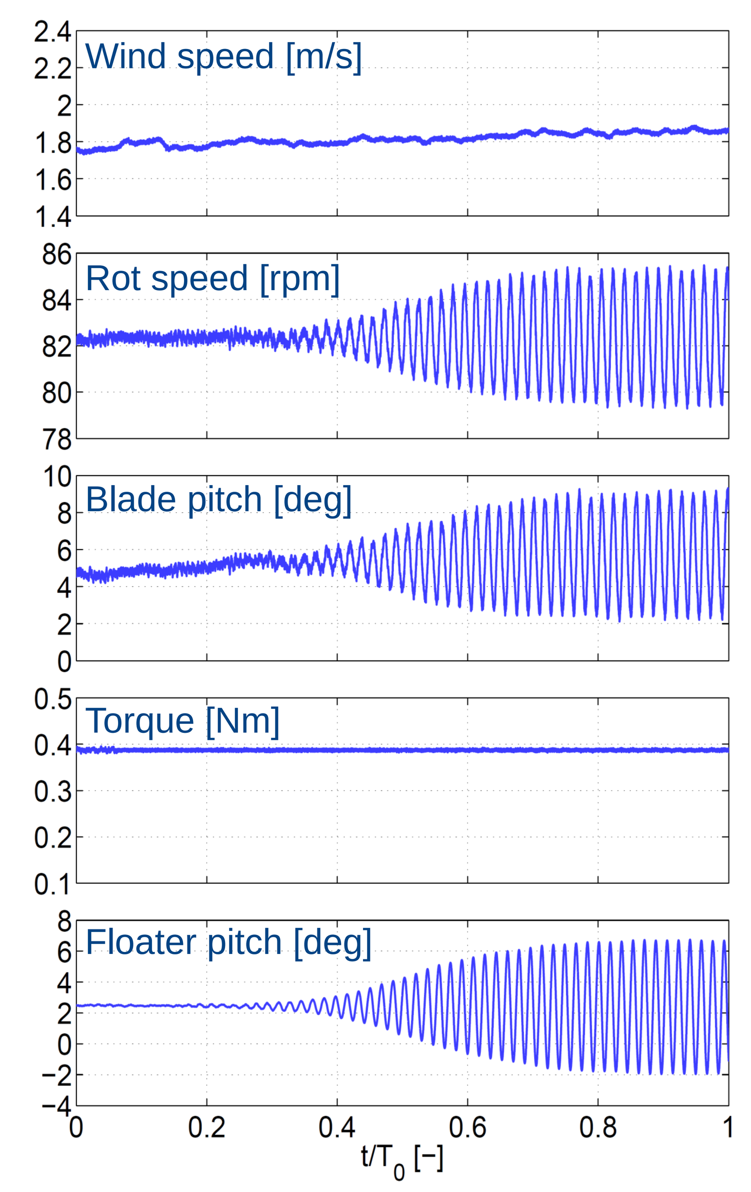


Fig.7 Negative damping
FOWT response with the conventional speed controller gain (see Fig.8)

Conclusions

We investigated effects of the gain parameters of the rotor speed control on the behaviour of the floater pitch motion. The instability of the FOWT response in pitch motion depends on controller bandwidth. The negative damped response appeared in the cases with high controller bandwidth. Even for the controller bandwidth as high as the conventional fixed bottom turbines, we validated the enhanced control method to suppress the negative damped response of the platform.

References

1. Larsen, T.J. and Hanson, T.D., "A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine," Journal of Physics: Conference Series 75 (2007) 012073, 2007.
2. Martin, H.R., "Development of a Scale Model Wind Turbine for Testing of Offshore Floating Wind Turbine Systems" Electronic Theses and Dissertations. Paper 1578, The University of Maine, 2011.
3. William E-J.R et al., "State of the Art Model Testing Techniques for Floating Wind Turbines," EWEA Offshore 2013.
4. Yoshimoto, H., et al., "Development of floating offshore substation and wind turbine for Fukushima FORWARD," Proc. International Symposium on Marine and Offshore Renewable Energy, 2013, Tokyo, Japan.
5. Fischer, B., "Reducing rotor speed variations of floating wind turbines by compensation of non-minimum phase zeros," EWEA 2012.