Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Structural Vibration Control of NREL 5.0 MW FOWT Using Optimal-Based MR Tuned Vibration Absorber

P. Martynowicz*, M. Santos**

**AGH University of Science and Technology, Department of Process Control, 30-059 Krakow, Poland (e-mail: pmartyn@agh.edu.pl).*
***Computer Architecture and Automatic Control, University Complutense of Madrid, 28040-Madrid (e-mail: msantos@ucm.es).*

Abstract: In this work, a National Renewable Energy Laboratory (NREL) 5.0 MW floating offshore wind turbine (FOWT) model equipped with nonlinear, magnetorheological (MR) tuned vibration absorber (TVA) is analysed. Several optimal-based MR damper control solutions are regarded against passive TVA configurations and the structure without the TVA system. Tower and barge/platform angular displacement amplitude frequency responses are compared, proving the efficiency and robustness of the adopted vibration reduction solutions, as well as their capability to minimise the amplitude of the vibrating structure, the demanded actuator (e.g. MR damper) force and stroke range.

Keywords: Structural vibration, optimal control, tuned vibration absorber, magnetorheological damper, floating offshore wind turbine, wind energy.

1. INTRODUCTION

Wind turbine technology is emerging as an eco-friendly and effective renewable power source. Offshore wind power has solved some of the limitation of on-land turbines. Still, offshore bottom-fixed wind platforms present some disadvantages that have led to propose new solutions.

Floating offshore wind turbines (FOWT) seem a promising technology as they are able to access deeper waters with stronger winds. But in order to make them economically viable it is necessary to reduce the mechanical loads induced by wind and waves on the structure. Moreover, from the control point of view, their dynamics is more complicated and strongly non-linear.

To face the problems due to structural vibration, different structural control solutions are being applied for slender structures. The use of tuned vibration absorbers (TVAs, also known as tuned mass dampers, TMD) has been successfully investigated. New active and semi-active control solutions are being proposed to reduce the loads of these floating devices.

In this paper, a magnetorheological (MR) tuned vibration absorber (TVA) device has been designed and tuned in order to minimise the vibration of the floating structure.

2. RELATED WORKS

Structural control has been applied to reduce vibration to different structures. Passive, semi-active and active structural control strategies are being proposed to decrease the fatigue of offshore wind turbines, both bottom-fixed and floating ones (Tomás-Rodriguez and Santos, 2019). Different semi-active control strategies have been applied to wind towers and to other structures, such as in Yu, Ma, & Falzarano (2010), where it was first applied to a one-story building under El-Centro earthquake, and was further applied to the dynamic response control of a fixed jacket offshore platform. The TVAs have been located at different parts of the wind turbine.

Among the different semi-active control strategies, magnetorheological (MR) dampers have been applied to offshore fixed-bottom wind turbines the last decade. For instance, Yu, Ma, & Falzarano (2010) applied a semi-active control strategy to a jacket offshore turbine in order to adjust the voltage/current of magnetorheological (MR) dampers to track the optimal/desired damping force by the Linear Quadratic Regulator (LQR) method.

The use of magnetorheological (MR) dampers to semi-actively control wind induced vibrations of a 1/20 scaled wind tower model is investigate in Caterino (2015). They apply a variable restraint made up of a cylindrical hinge, two springs and two prototype MR devices at the base of the model, that are modified in real time according to the instantaneous response of the tower. The two proposed semi-active control technique are able to reduce the base bending stress and top displacement of the tower. This work was based in a previous one (Caterino et al., 2014), where the same semi-active control system based on the use of smart magnetorheological (MR) dampers to control the structural response of a wind turbine was tested in a 1/20 scale model at the Denmark Technical University (DTU). The control algorithm instantaneously commands the MR during the motion, modifying its mechanical properties to modulate the reactive force as needed to achieve the performance goals.

A MR damper has been also tested on a laboratory test rig of wind turbine tower-nacelle (Martynowicz, 2016, 2017, 2019a, 2019b). In this case, the horizontally aligned TVA with magnetorheological (MR) damper is located also at the top of

Copyright lies with the authors

the rod (in the nacelle system). The MR damper real-time control algorithms, including 'ground hook' control and its modification, sliding mode control, linear and nonlinear, damping, and adaptive solutions are compared to the open-loop case with various constant MR damper input current values and system without MR TVA with promising results.

Intelligent control has been also applied to implement semi-active structural control to offshore platforms. In Ji and Yin (2007), fuzzy magnetorheological controller was adopted to reduce effectively the dynamic responses of the offshore turbine. Taking the error of offshore platform displacement responses and error variety as inputs, and the optimal control force as output, the optimal fuzzy controller is designed. Then, a semi-active control strategy is used to revise the output control force, which approximates to the optimal active control force calculated by the fuzzy control strategy.

A recent paper by Rahman et al. (2019) proposes a smart semi-active vibration control system using magnetorheological (MR) dampers where PID and PI feedback controllers are optimized with nature-inspired algorithms, using ant colony optimization (ACO) algorithm. The placement of the MR damper on the tower is also investigated to ensure structural balance and optimal desired force from the MR damper. The simulation results show that the proposed semi-active PID-ACO control strategy can significantly reduce vibration on the wind turbine tower under different frequencies. The proposed PID-ACO control strategy and optimal MR damper position is also implemented on a lab-scaled wind turbine tower model.

Nevertheless, the application of this type of structural control to floating wind turbines is more recent and scarcer. Having said that, Dinh, Basu and Nagarajaih (2016) applied a semi-active control of TMD placed in each blade, in the nacelle and on the spar of a spar-type floating offshore wind turbine. A Short Time Fourier Transform algorithm is used for semi-active control of the TMDs. Authors state that, except for excessively large strokes of the nacelle TMD, the semi-active algorithm is considerably more effective than the passive one in all cases and its effectiveness is restricted by the low-frequency nature of the nacelle and the spar responses.

Park et al. (2016) showed the effects of a passive tuned mass damper and a semi-active tuned mass damper, located at the tower top of a GE Haliade 150–6MW wind turbine located on the Glosten Pelastar tension-leg platform (TLP). Semi-active control was defined using an "on-off" TMD damping based on a "ground-hook" control law, for two different water depths. The results showed that semi-active control can be an effective strategy to further reduce loads and reduce the TMD stroke in deep water configurations, but are less effective in shallow water.

An example of the application of a tuned liquid column damper (TLCD) is shown in Coudurier, Lepreux, and Petit (2015). The semi-active control strategy consists in adapting the damping coefficient of the TLCD in real time to reduce the pitch oscillations of a typical 5000 tons barge floating wind turbine excited by a JONSWAP irregular wave.

The reduction of the structural load for stabilizing a floating wind turbine with semi-active structural control is realized in Wang et al. (2019) by replacing the damper in passive TMD with the magnetorheological (MR) damper whose parameters can be changed by altering the voltage applied to it. The simulation results show that the semi-active control method has a good damping effect, which mitigates much of the structural load with respect to the passive structural control.

3. SIMULATION MODEL

This work considers the non-linear floating wind turbine (Fig. 1) presented in Stewart and Lackner (2014). Particularly, we focused on the 3DOF National Renewable Energy Laboratory (NREL) 5.0 MW floating offshore wind turbine (FOWT) barge-type.

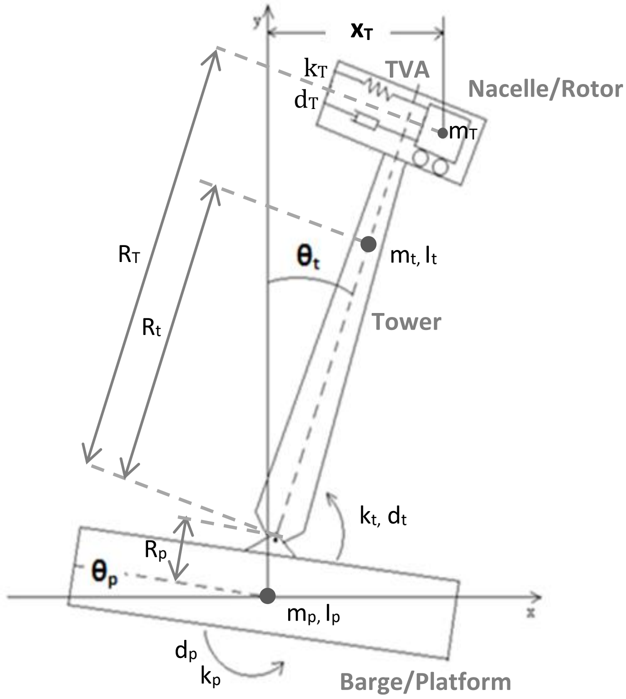

Fig. 1. Barge-type wind turbine (Tomas-R. and Santos, 2019)

We analyse a simplified model of a barge-type marine wind turbine, where aerodynamic load, or sea waves thrust and mooring forces of the catenary lines are reduced to resultant horizontal concentrated forces applied to a rotor (F_r force with lever arm R_{rf}, where $R_{rf} \approx R_T$), or to a platform (F_p force with lever arm R_{pf}), respectively. This simplified model includes disturbances in a dynamics of a platform and a tower, without modelling a nature of these disturbing forces – the model does not focus on turbine blades or mooring lines dynamics, while their contribution to a barge-tower-nacelle system oscillations and fatigue is represented by concentrated excitation forces.

The model represented in the following differential equations contains the terms that correspond to the hydrostatic restoration forces and to the water damping (included in the model) as a rotating spring (k_p) and shock absorber (d_p) attached to the platform. A linear approximation can be used for small angular displacements (<10º), as it is the case for these floating structures. The stiffness and damping of the tower are also represented by a spring and a damper with coefficients k_t, and d_t, respectively (Fig. 1).

The linear version of the dynamic model is expressed by:

$$\begin{cases} I_t\ddot{\theta}_t = m_t g R_t \theta_t - k_t(\theta_t - \theta_p) - d_t(\dot{\theta}_t - \dot{\theta}_p) \\ \quad -m_T g(R_T\theta_t - x_T) - k_T R_T(R_T\theta_t - x_T) \\ \quad -d_T R_T(R_T\dot{\theta}_t - \dot{x}_T) + F_r R_{rf} \\ I_p\ddot{\theta}_p = -d_p\dot{\theta}_p - k_p\theta_p - m_p g R_p\theta_p \\ \quad +k_t(\theta_t - \theta_p) + d_t(\dot{\theta}_t - \dot{\theta}_p) + F_p R_{pf} \\ m_T\ddot{x}_T = k_T(R_T\theta_t - x_T) + m_T g\theta_t \\ \quad +d_T(R_T\dot{\theta}_t - \dot{x}_T) \end{cases} \tag{1}$$

where generalized coordinates (three degrees of freedom of the FOWT model) are a barge/platform absolute pitch angle θ_p, a tower system (including a nacelle and a rotor) absolute angular displacement θ_t, and a TVA mass absolute displacement x_T. The k_T and d_T terms represent the TVA spring stiffness and damping coefficient, respectively.

This linear approximation of the dynamic model has been validated with the non-linear full degree-of-freedom model FAST-SC (Villoslada et al., 2020).

Table 1 and Table 2 show the main properties of the particular FOWT we are working with.

Table 1. Gross Properties of the NREL 5-MW Baseline Wind Turbine (Jonkman et al., 2009)

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Rotor Diameter	126 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3.0, 11.4, 25.0 m/s
Cut-In, Rated Rotor Speed	6.9, 12.1 rpm
Rotor Mass Nacelle Mass (m_t) Tower Mass	110 000 kg 240 000 kg 347 460 kg
Tower-Nacelle-Rotor CM Height (R_t)	64.0 m

Table 2. Gross Properties of the ITI Energy Barge (Vijfhuizen, 2006)

Size (W×L×H)	40 × 40 × 10 m
Moonpool (W×L×H)	10 × 10 × 10 m
Draft, Freeboard	4, 6 m
Water Displacement	6 000 m3
Mass, Including Ballast (m_p)	5 452 000 kg
Centre of Mass (CM) Below SWL	0.282 m

The 3 DOF NREL 5.0 MW FOWT model equipped with MR TVA, using hyperbolic tangent MR damper model in the form of:

$$F_{MR} = F_c \tanh\left\{\nu\left(x_t + \dot{x}_t - x_T - \dot{x}_T\right)\right\} + c_0\left(x_t + \dot{x}_t - x_T - \dot{x}_T\right) \tag{2}$$

was embedded in *MATLAB/Simulink* environment. In (2), F_{MR} is the force produced by the MR damper, F_c and c_0 are current-dependent friction force and viscous damping coefficients, ν is a scaling parameter, while x_t and $\dot{x}_t$ are tower top x-axis absolute displacement along with its time derivative. The assumed MR damper model parameters are listed in Table 3.

Table 3. The MR damper model parameters

Parameter	Value
C_1	7068
C_2	171
C_3	$54.72 \cdot 10^3$
C_4	$15.96 \cdot 10^3$
ν	$1.3 \cdot 10^3$

4. MR TVA CONTROL SOLUTIONS

Most of the on-line and real-time vibration attenuation systems using highly nonlinear elements as MR dampers, including MR TVAs, are based on direct two-level (bang-bang) control such as displacement or velocity sky-hook/ground-hook or sliding mode control, fuzzy logic, heuristic algorithms, or the cascade systems in which the outer loop is calculating the required value of the damper resistance force (with the use of e.g. optimal control / LQR / LQG or H_∞ methods, Lyapunov stability theory, sliding mode control, adaptive tuning of TVA dynamical stiffness and damping, etc.), and the inner loop deals with the tracking of the required force by appropriate control of the voltage in the damper winding (Jansen and Dyke, 2000; Ji and Yin, 2007; Yu et al., 2010; Caterino, 2015; Coudurier et al. 2015; Park et al., 2016; Dinh et al., 2016; Wang et al., 2019). Although the control determined by the outer loop methods can be directly applied using active systems, it cannot be simply implemented using semi-active (e.g. MR) elements – in this case the internal loop of the cascade algorithm switches the control function, emulating the required force value only if it is dissipative in nature. So, common cascade solutions have the main disadvantage of not being able to reproduce the required force profile due to the characteristics of the MR damper.

In this work, several optimal-based approaches to FOWT structural vibration attenuation were investigated against passive TVA implementations. The common approach to optimal control of nonlinear systems is offline computation of the optimal solution. However, so determined open loop control suffers from lack of robustness to uncertainties (e.g. unmodelled dynamics, perturbations of external forces or initial conditions), and thus perturbation control techniques are often used. However, proper linearization may be an issue for highly nonlinear systems with implicit relations between state, co-state and control.

Recently, the Pontriagin-maximum-principle-based nonlinear vibration control concepts that produce directly MR damper control current i_{MR} (*not* the demanded force, thus force tracking algorithm that results in control inaccuracy is entirely omitted) were developed and verified both numerically and experimentally (Martynowicz, 2019a, 2019b). These concepts, including one-step optimal control, quasi-optimal control, and optimal-based modified 'ground-hook' law, can be directly implemented in online and real-time feedback control for every excitation type, what is a limitation of some other known solutions. Moreover, two-level modified 'ground-hook' law (*Section 1.1*) was previously proved to be the most effective (Martynowicz, 2016, 2017) in MR TVA control, whereas (quasi-)optimal control approach is an origin of this method that provides an additional potential (*Section 1.2*). These two, low and moderate calculation-demanding, yet very efficient approaches were implemented for NREL 5.0 MW FOWT model with MR TVA. All the details of control implementation, including mathematical formulations, are covered in (Martynowicz, 2019a, 2019b).

1.1 Optimal-based modified 'ground-hook' law

Based on the optimal control derivation, a simple two-level control (modified displacement 'ground-hook' law, designated by *Mod.GND*) was proposed (3), not requiring optimal control two-point boundary value problem solving, nor the implementation of both the Hamiltonian maximization condition and state/co-state dynamics:

$$i_{MR} = \begin{cases} i^{\max}, & \text{if } x_t F_{MR} \geq 0 \\ 0, & \text{if } x_t F_{MR} < 0 \end{cases} \tag{3}$$

where $i^{\max}$ is a maximum MR damper current. This method minimizes only the displacement/deflection amplitude of the protected structure, but it is possible to adapt it to optimize other operating quantities.

1.2 Quasi-optimal control

A simplified optimal control procedure, without two-point boundary value problem solving necessity, was regarded here (designated by *OPT*). On-line/real-time implementation of the Hamiltonian maximization condition, including state/co-state dynamics is needed. The analysis of the error of this approach and the results of the simulation tests prove that this method is valid except for a limited number of time points – when the deflection of the protected structure changes sign – and the quality of vibration control does not differ from the quality of one-step optimal control (incorporating two-point boundary value problem solving in each sampling step), assuming the appropriate sampling frequency. Depending on the complexity of the regarded quality index, it is possible to minimize the amplitude of the deflection/displacement of the vibrating system (possibly also its acceleration, potential and/or kinetic energy, etc.), while minimizing the required MR damper force F_{MR}, the required current in its winding i_{MR} and/or the amplitude of the damper stroke x_t–x_T (i.e. MR TVA relative displacement). We assumed here the quality index in the form (4):

$$g(x,u) = g_{11}x_t^2 + g_{13}(x_t - x_T)^2 + g_{21}i_{MR}^{\,2}(u) + g_{22}F_{MR}^{\,2}(x,u) \tag{4}$$

where g_{11}=10^{18}, g_{13}=0, g_{21}=4, and g_{22}=0 are respective weighting factors to account for (minimize) the tower top horizontal displacement, MR damper stroke, current, and force.

5. RESULTS

The analysed FOWT was subjected to horizontal disturbance F_r of amplitude 85 kN, and (0.05, 0.60) Hz frequency range (incorporating platform pitch, tower bending, and platform – tower system collective fundamental vibration mode as well as typical waves, rotor and blade passing excitations frequencies), applied to the rotor, modelling the wind excitation. The analyses carried out for the disturbing force applied to the barge (F_p) yielded the results that are consistent with the characteristics presented below.

The TVA was tuned either to the tower system (including nacelle and rotor masses) fundamental bending frequency of 0.308 Hz – the common approach for land-based or offshore monopile wind turbine structures, or to the platform pitch frequency of 0.165 Hz (annotations in figure legends: *Ptfm*). The latter TVA tuning corresponds to some other studies, e.g. (Tomas-Rodriguez and Santos, 2020). Tuning the TVA to the platform – tower system collective fundamental vibration mode did not yield favourable results, however, more analyses will be carried out regarding, in particular, MR damper electromechanical design and parameters adjusting.

The frequency responses of the tower system (designated by *Twr*, including nacelle and rotor masses) absolute angular displacement amplitude, the platform (designated by *Ptfm*) absolute pitch angle amplitude, the MR TVA stroke (relative displacement) amplitude as well as the MR damper maximum force are presented in Figs. 2-8. The MR TVA control solutions (*Mod.GND* and *OPT*) results are compared with responses of passive configurations with constant MR damper current (*0.0 A*, *0.2 A*, and *0.5 A*), and responses of the FOWT structure without TVA system (*no TVA*).

When observing Figs. 2-5 it is evident that both controlled, semiactive configurations (*Mod.GND*/*OPT*) are the most desirable. The maximum amplitude of the angular displacement of the tower system is reduced more than fivefold in relation to the structure without TVA.

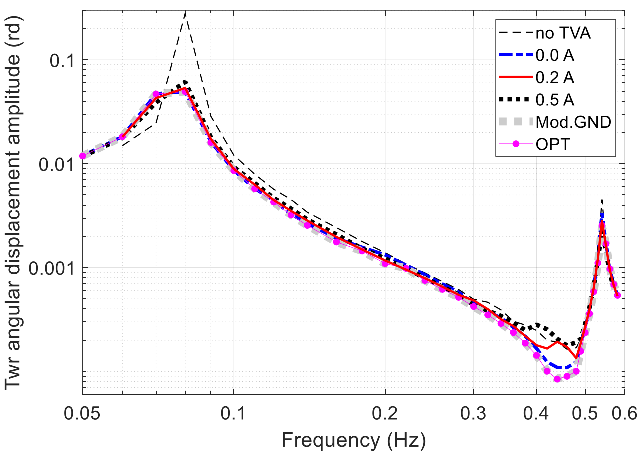

Fig. 2. *Twr* angular displacement amplitude; TVA tuned to the platform pitch frequency.

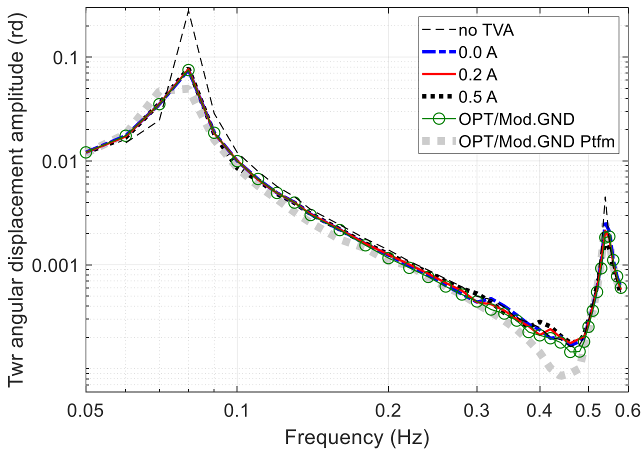

Fig. 3. *Twr* angular displacement amplitude; if not otherwise stated in the legend, TVA tuned to the tower system fundamental bending frequency.

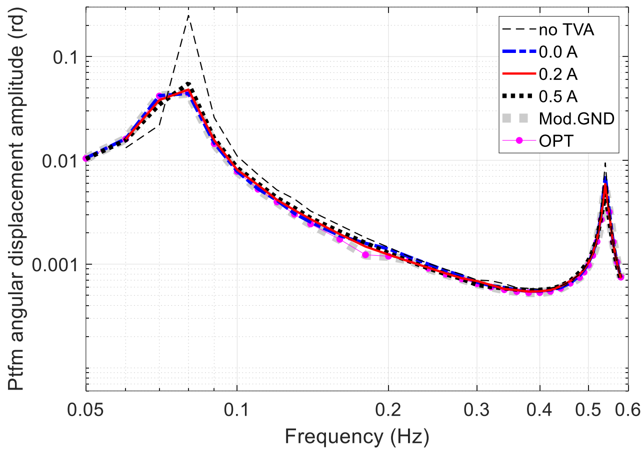

Fig. 4. *Ptfm* angular displacement amplitude; TVA tuned to the platform pitch frequency.

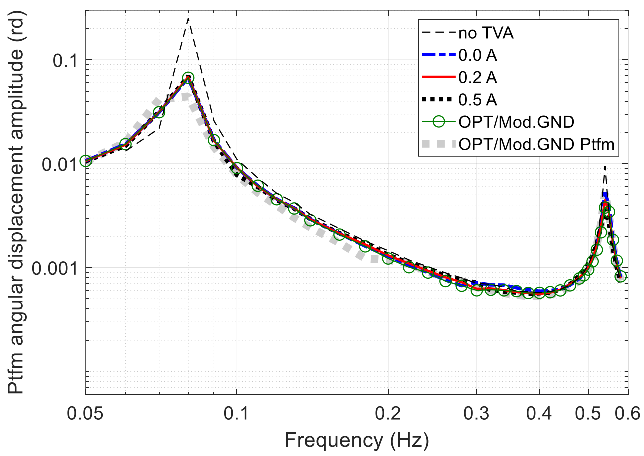

Fig. 5. *Ptfm* angular displacement amplitude; if not otherwise stated in the legend, TVA tuned to the tower system fundamental bending frequency.

The *Mod.GND* and *OPT* control solutions produce unnoticeable response differences (see Figs. 2 and 4) for the case when the structure displacement x_t minimisation is the sole control objective (g_{13}=0, g_{22}=0), thus some their frequency response curves are grouped. Furthermore, Figs. 3 and 5 prove that TVA tuning to the platform pitch frequency is a better solution than tuning it to the tower system fundamental bending frequency – the tower system angular displacement amplitude responses of the former are more favourable (Fig. 3); this also concerns the platform angular displacement amplitudes (Fig. 5).

Figs. 6-8 present influence of g_{13} and g_{22} weighting factors on the tower system angular displacement, MR TVA stroke, and MR damper force amplitude responses for the preferred TVA tuning configuration (TVA tuned to the platform pitch frequency). When assuming $g_{13}=10^{17}$, the MR TVA stroke amplitude is reduced in considerable frequency range (see Fig. 7) at the cost of small performance degradation (Fig. 6) and transferred MR damper force demand (Fig. 8), comparing to g_{13}=0 case (i.e. *OPT*/*Mod.GND* curves). When assuming $g_{22}=10^{9}$, the MR damper force demand is reduced significantly (even sevenfold), along with the MR TVA stroke amplitude reduction, in wide frequency ranges (see Figs. 7, 8) at the cost of small performance degradation (Fig. 6), comparing to g_{22}=0 configuration (i.e. *OPT*/*Mod.GND*).

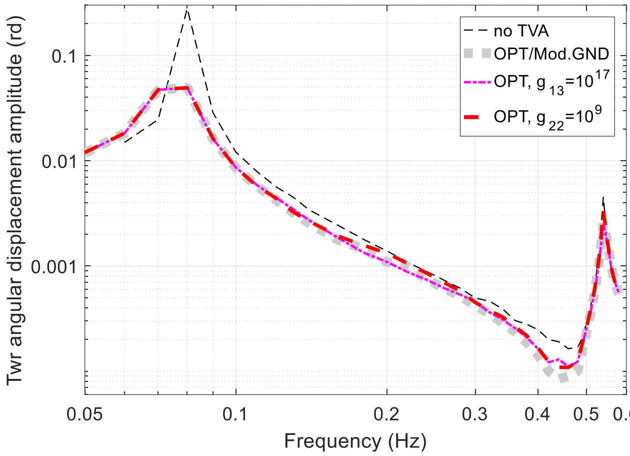

Fig. 6. *Twr* angular displacement amplitude; TVA tuned to the platform pitch frequency.

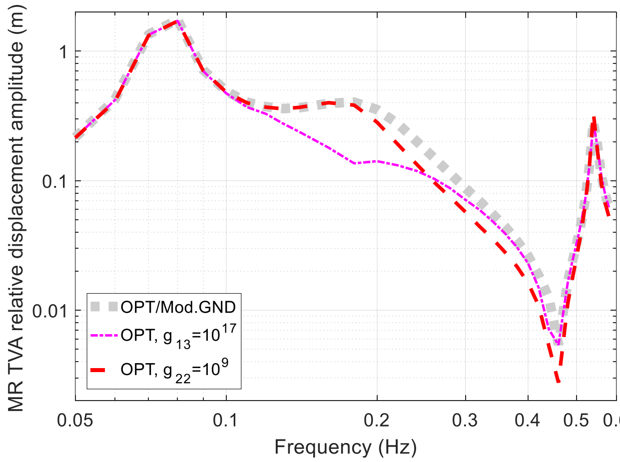

Fig. 7. MR TVA stroke (relative displacement) amplitude; TVA tuned to the platform pitch frequency.

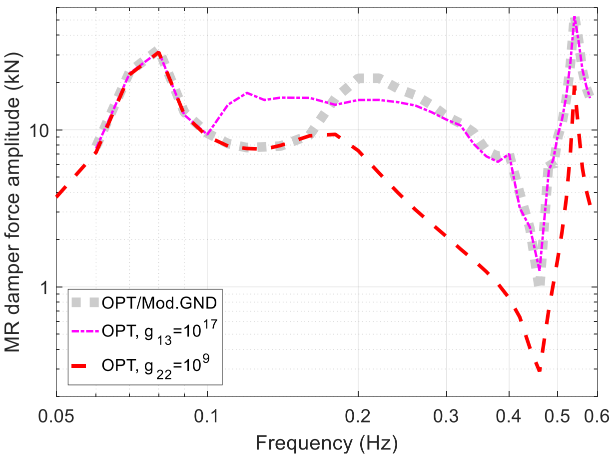

Fig. 8. MR damper force amplitude; TVA tuned to the platform pitch frequency.

6. CONCLUSIONS

The developed FOWT vibration reduction solutions, using controlled semiactive MR TVA, are characterized by high efficiency in comparison with passive configurations. The obtained results prove the quality and robustness of the adopted solutions, and their capability to *minimise* pitching amplitude of the vibrating structure (yielding improved wind energy extraction) as well as MR damper force and/or stroke amplitude. No offline calculations, MR damper force tracking, excitations/disturbances assumption, or continuous dominant frequency determination is necessary for proper on-line/real-time implementation; moreover, all of the actuator dynamics and force constraints are embedded in the control technique, thus the solution is optimal or suboptimal for the assumed actuator (that may be e.g. MR damper), respecting its limitations.

More analyses are expected concerning MR TVA adjusting.

ACKNOWLEDGEMENTS

This work was partially supported by the Spanish Ministry of Science, Innovation and Universities under Project number RTI2018-094902-B-C21.

REFERENCES

Caterino, N., Georgakis, C.T., Trinchillo, F., Occhiuzzi, A. (2014). A semi-active control system for wind turbines. In *Wind Turbine Control and Monitoring* 375-407, Springer.

Caterino, N. (2015). Semi-active control of a wind turbine via magnetorheological dampers. *Journal of Sound and Vibration*, 345, 1-17.

Coudurier, C., Lepreux, O., and Petit, N. (2015). Passive and semi-active control of an offshore floating wind turbine using a tuned liquid column damper. *IFAC-PapersOnLine*, 48(16), 241-247.

Dinh, V.N., Basu, B., Nagarajaiah, S. (2016). Semi-active control of vibrations of spar type floating offshore wind turbines. *Smart Structural Systems*, 18(4), 683-705.

Ji, C., and Yin, Q. (2007). Study a on fuzzy MR damper vibration control strategy for offshore platforms. In *ASME 2007 26th Int. Conf. on Offshore Mechanics and Arctic Engineering* (pp. 363-368).

Jansen, L.M., and Dyke, S.J. (2000). Semiactive control strategies for MR dampers: comparative study. *Journal of Engineering Mechanics*, 126(8), 795-803.

Jonkman, J., Butterfield, S., Musial, W., and Scott, G. (2009). *Definition of a 5-MW reference wind turbine for offshore system development* (NREL/TP-500-38060). CO, US.

Martynowicz, P. (2016). Study of vibration control using laboratory test rig of wind turbine tower-nacelle system with MR damper based tuned vibration absorber. *Bulletin of the Polish Academy of Sciences Technical Sciences*, 64(2), 347-359.

Martynowicz, P. (2017). Vibration control of wind turbine tower-nacelle model with magnetorheological tuned vibration absorber. *Journal of Vibration and Control*, 23(20), 3468-3489.

Martynowicz, P. (2019a). Nonlinear optimal-based vibration control for systems with MR tuned vibration absorbers. *Journal of Low Frequency Noise, Vibration and Active Control*, 38(3-4), 1607-1628.

Martynowicz, P. (2019b). Real-time implementation of nonlinear optimal-based vibration control for a wind turbine model. *Journal of Low Frequency Noise, Vibration and Active Control*, 38(3-4), 1635-1650.

Park, S., Lackner, M.A., Cross-Whiter, J., Tsouroukdissian, A.R., and La Cava, W. (2016). An investigation of passive and semi-active tuned mass dampers for a tension leg platform floating offshore wind turbine in ULS conditions. In *ASME 2016 35th Int. Conf. on Ocean, Offshore and Arctic Engineering*.

Rahman, M., Ong, Z.C., Chong, W.T., et al. (2019). Smart Semi-active PID-ACO control strategy for tower vibration reduction in wind turbines with MR damper. *Earthquake Engineering and Engineering Vibration*, 18(4), 887-902.

Stewart, G.M., and Lackner, M.A. (2011). The effect of actuator dynamics on active structural control of offshore wind turbines. Engineering Structures, 33(5), 1807-1816.

Stewart, G.M., and Lackner, M.A. (2014). The impact of passive tuned mass dampers and wind–wave misalignment on offshore wind turbine loads. *Engineering Structures*, 73, 54-61.

Tomas-Rodriguez, M., and Santos, M. (2019). Modelling and control of floating offshore wind turbines. *Revista Iberoamericana de Automática e Informática Industrial*, 16(4), 381-390.

Vijfhuizen, W.J.M. (2006). *Design of a wind and wave power barge*, Ph.D, Naval Architecture and Mechanical Engineering Dept., Glasgow and Strathclyde Universities.

Villoslada D., Santos M., Tomás-Rodríguez, M. (2020). Inerter-based passive structural control for barge floating offshore wind turbines. *IFAC PapersOnLine Congress*.

Wang, L., Liang, Z., Cai, M., Zhang, Y. (2019). Adaptive structural control of floating wind turbine with application of MR damper. *Energy Procedia* 158, 254-259.

Yu, X., Ma, T., and Falzarano, J.M. (2010). Application of a new semi-active control strategy to dynamic response control of an offshore platform using MR dampers. In *ASME 2010 29th Int. Conf. on Ocean, Offshore and Arctic Engineering* (pp. 731-736).