A semi-active rocking system for wind turbines under extreme wind loads

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ABSTRACT

In the last decades, the negative impact of the use of fossil fuels on the environment has lead to a boom in the production of wind turbines. Then, wind turbine heights are progressively increasing in order to take advantage of the smoother winds at higher altitude. But, this has led to an increased demand to control tower forces. The application of a semi-active (SA) control system is herein proposed and discussed. Its aim is to limit bending moment demand at the base of a wind turbine by relaxing the base restraint of the turbine's tower, without increasing the top displacement, thanks to the sharp increase of dissipated energy in selected intervals of time and a consequent change in tower dynamic properties. The proposed SA control system reproduces a variable restraint at the base that changes in real time its mechanical properties according to the instantaneous response of the turbine's tower. This smart restraint is made of a central smooth hinge, elastic springs and SA magnetorheological dampers driven by a properly designed control algorithm. A commercial 105 m tall wind turbine has been assumed as a case study. Several numerical simulations have been performed with reference to an extreme load, aimed at establishing a procedure for the optimal calibration of the control algorithm according to the specific case, finally proving the actual potential of the proposed control technique in reducing the structural demand with respect to the "fixed base" structure.

Keywords: *Semi-active control, rocking control system, wind turbine, magnetorheological damper*

1 INTRODUCTION

Due to the increasing height of wind turbines, wind turbine manufacturers have become ever more interested in methods for reducing or limiting tower base moments. There are two main reasons for this. First, the tower diameters at the base are increasing beyond the point where they can be fabricated off-site and shipped to the location of installation, so that construction costs and complexity are significantly increasing. Second, the tower diameters and associated base moments of newer wind turbines far exceed those of existing wind turbines that the newer ones hope to replace. Therefore, existing foundations cannot be utilized and new or strengthened foundations need to be constructed.

The maximum base moments of a wind-turbine are generated by very specific, almost improbable, load cases. These include the load cases which involve extreme gusts of wind

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combined with emergency shut-down procedures. All the extreme load cases are short duration impulse loads which generate maximum expected tower base moments; this cannot be combated using traditional damping devices. As damping is generally considered ineffective for impact type loading, a variable tower stiffness and damping approach needs to be followed. In this paper, the concept of an adaptive wind turbine tower is examined, where the adaptation is realized through the implementation of a semi-active (SA) control system.

Chen and Georgakis [1] performed an experimental analysis of a 1/20-scale wind tower model equipped with a passive rolling-ball damper to reduce vibrations. Such damper consists of a glass container placed at the top of the model and having one or more steel balls inside. Different configurations have been tested, changing the geometry of the container (one or two layers) and the number of balls (one to six) placed inside, showing a significant reduction of the peak value and standard deviation of top displacement and base bending moment. The same authors [2] tested the same model using water rather than steel balls inside the glass container, i.e. realizing a spherical tuned liquid damper. The optimal degree of filling with water (1-2% of the total generalized mass of the system) has been found as leading to the maximum reduction of structural demand.

As regard active/semi-active control strategies from literature related to wind turbines, Karimi et al. [3] and Luo et al. [4] propose a SA control technique for floating wind turbines with TLCD. This device, generally used as a passive damper, turns into a SA device using a controllable valve. The orifice opening is real time adapted according to the structure response and loading conditions, with a control logic based on a $H\infty$ feedback methodology. Lackner and Rotea [5] investigate the effectiveness of an optimal passive TMD and of a hybrid mass damper (HMD, i.e. a TMD improved with the addition of a controlled force actuator) in reducing fatigue loads due to bending moment at the base of the tower, showing a percentage reduction of about 10% and 30% respectively due to each of the two proposed systems. Kirkegaard et al. [6] have been the first to explore the use of magnetorheological (MR) dampers to control a wind turbine, assuming such type of smart device to be installed, in a vertical position, between the base and the top of the tower. Even hard to be implemented in a real case, the numerical simulations show good results. Experimental results are also made available by the authors, unfortunately referred to the passive use (constant voltage fed to the MR damper) of the device only.

The authors recently proposed a SA control system based on the application of MR devices to realize a time-variant base restraint whose 'stiffness' can be driven in real time by a properly written control logic [7, 8]. The controller has to be programmed to instantaneously calibrate the MR devices installed at the base of the tower in order to reduce the base bending moment, relaxing in selected intervals of time the base restraint. Again, the control logic has to hold the top displacement within acceptable values so as to avoid significant, detrimental second order effects. At the laboratory of the Denmark Technical University (DTU) in Copenaghen, some preliminary shaking table tests of a wind turbine tower model semi-actively controlled as above has been recently performed by the authors. After the formulation of the above idea, a finite element model of the structure has been calibrated so as to develop several numerical simulations addressed to optimally calibrate the control logic properly designed for such kind of applications.

2 A SEMI-ACTIVE ROCKING SYSTEM FOR HIGH WIND TURBINES

A semi-active rocking system, exploiting controllable fluid based devices, is proposed as base restraint of the high-rise wind turbine towers, with the aim of reducing their wind induced structural demand. This is schematically shown in Fig. 1, where the uncontrolled wind turbine, fully restrained at the base, is modeled as a single degree of freedom dynamic system (Fig. 1(a)), having top mass m, stiffness k_T and inherent damping c_T. In order to control the structural demand, the authors proposed to replace the perfectly rigid base restraint with a smart one that is able to instantaneously become more or less "stiff", during the motion. Fig. 1(b) just sketches that it is possible to realize this idea by installing at the base of the tower a smooth hinge, a rotational spring (of stiffness k_ϕ) and a rotational variable damper whose damping constant c_ϕ can be driven in real time by a control algorithm. The same result can be practically produced by mounting two vertical linear springs (k_s) placed at a certain distance (l_s) from the hinge and two vertical variable dampers (c_d) at a distance l_d from the central hinge (Fig. 1(c)). SA magnetorheological (MR) dampers were considered as smart devices within the proposed control system: by varying the MR dampers' mechanical properties according to a given control logic, the base control system is able to realize a real time regulation of the system's stiffness. When a low value is imposed to the base damping, the base restraint is less 'stiff', so that the structure is able to relax by converting its potential energy into kinetic energy, and the bending moment at the base is reduced. It was expected that a direct consequence of controlling the demand of base bending stress can be an increase of total top displacement demand. Therefore, the SA base control system was thought to reduce base stress, by restraining the increase of top displacements within certain limits to control second order effects. The springs have also the role to induce the recentering of the tower to the initial position at the end of a severe wind-induced excitation.

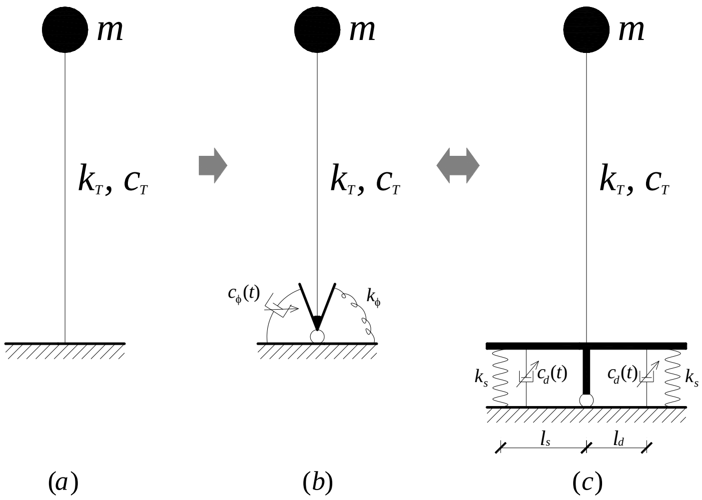

Figure 1 - Basic idea of SA rocking control of a wind turbine.

Predefined control algorithm for such specific application cannot be found in literature, where a significant number of SA controllers, still for MR dampers, are formulated to protect structures against strong earthquakes rather than wind. Therefore, a specific control algorithm, based on a simple, physical approach, has been formulated by the authors [7, 8] to instantaneously decide the system's base restraint configuration. It deals with a bang-bang controller, switching back and forth from an OFF state (intensity of current $i = i_{\min}$, i.e. the minimum current set to be given to the dampers) to an ON state ($i = i_{\max}$, i.e. the maximum assumed value for the current) according to a logic aiming to control both the base stress and the top displacement. Practically, the objective of the control algorithm was to achieve a trade-off between two contradictory objectives: a limit value for the base stress $\sigma_{\lim}$ and a limit value for the top displacement $x_{\lim}$. The following instructions are applied:

$$\begin{array}{lll} \text{a)} & \text{if } |\sigma(t)| < \sigma_{\lim} & \rightarrow \; ON \\ \text{b)} & \text{if } |\sigma(t)| \geq \sigma_{\lim} \text{ and } |x(t)| < x_{\lim} & \rightarrow \; OFF \\ \text{c)} & \text{if } |\sigma(t)| \geq \sigma_{\lim} \text{ and } |x(t)| \geq x_{\lim} \text{ and } x(t)\cdot \dot{x}(t) > 0 & \rightarrow \; ON \\ \text{d)} & \text{if } |\sigma(t)| \geq \sigma_{\lim} \text{ and } |x(t)| \geq x_{\lim} \text{ and } x(t)\cdot \dot{x}(t) \leq 0 & \rightarrow \; OFF \end{array} \quad (1)$$

where $\sigma(t)$, $x(t)$ and $\dot{x}(t)$ are respectively the value of stress at the base, top displacement and top velocity at the instant of time t. In other words, the controller keeps 'stiffer' the base restraint (ON) until the stress exceeds the limit value $\sigma_{\lim}$, whereas 'relaxes' it (OFF) when this limit is overpassed and the displacement falls within the limit of acceptability x_{lim}. When both stress and displacement are beyond the respective threshold values, the controller switches ON the dampers if the displacement is going towards a larger value, so trying to damp or even invert the displacement's trend; otherwise it switches OFF the MR devices to make them collaborating to both stress and displacement reduction.

By considering the physical basis of the control logic, it is expected that, when a large value of σ_{lim} is adopted (i.e. less but not so far from the maximum value of base stress in fixed base conditions), a moderate reduction of base stress is achievable, while top displacement demand may increase significantly. This is caused by a limited number of SA operations, so that the dissipation phases are concentrated in much small intervals of time, not effective in reducing significantly the response in displacement. In other words, the instantaneous relaxing of the base restraint is able to limit the top displacement response, only when a significant dissipation of energy occurs. Vice versa, when smaller values of σ_{lim} are used, the system benefits from a greater dissipation of energy and, depending also on the assumed value for x_{lim}, may behave better from both points of view, i.e. base stress and top displacement.

The application of the proposed control algorithm requires the definition of rational criteria to optimally calibrate the parameters involved in (σ_{lim} and x_{lim}). A large numerical campaign has been performed with reference to a case study real structure, aiming to investigate the role each parameter has regarding the structural response, and to learn a possible procedure to calibrate them aiming at achieving the maximum reduction of base stress and top displacement demands.

3 CALIBRATION OF CONTROLLER FOR A REAL STRUCTURE

A calibration procedure is proposed in the following, in order to provide the optimal choice of values to be assigned to the parameters (σ_{lim} and x_{lim}) involved in the control algorithm. The first step is developing a finite element model of the structure to be examined, able to simulate both fixed base (FB) and SA controlled configurations. With reference to a given wind load, the structural response in the FB case has to be computed. Then, a wide number of SA numerical simulations has to be designed and performed. The analysis of results using a constrained optimization approach allows to single out the optimal configuration of the controller able to achieve the maximum reduction of base stress while not producing increasing of top displacement with respect to the FB case. An application of this procedure is showed in the following for a specific case study.

3.1 Case study: a real 3MW wind turbine.

The case study structure is a prototype real wind turbine. It is a 3 MW wind turbine with horizontal power transmission axle, 102.4 m tall, with a variable hollow circular cross section whose external diameter is variable from 2.30 m (top) to 4.15 m (bottom), and whose thickness is variable from 14 mm (top) to 40 mm (bottom). A lumped mass of 111 t is placed at the top of the tower. The base of the prototype structure is highly stiff and is supported in the middle by a cylindrical steel hinge. On both sides of the base, one cylindrical spring (1417 kN/m stiff) and one SA MR damper are installed. The assembly "elastic springs + SA MR dampers", whose elements are placed in parallel at the base of the tower, just represents the smart base restraint proposed by the authors to control the dynamic behaviour of the structure. An extreme operating gust loading has been considered in the following as reference wind action: a sharp increase, then decrease in wind speed within a short period of time. Chen and Georgakis [1] defined an equivalent base acceleration time history (Fig. 2), that is the base input that would provide the same top mass response of the real fixed base structure subjected to the wind action.

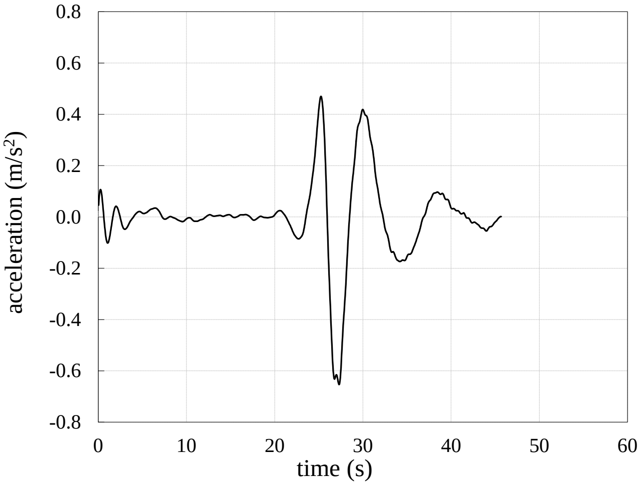

Figure 2 - Equivalent base acceleration time history for the wind load case.

3.2 Numerical model

A finite element model has been developed in Matlab environment to simulate the dynamic behavior of the case study real structure. It consists in 37 elements: 36 elements simulate the tower with variable hollow circular cross section (along the height, a variable diameter from 4.15 m to 2.30 m and a variable thickness from 40 mm to 14 mm), while the last element (37th) is more rigid (a double second moment of inertia is assigned) and represents the connection of the top of the tower to the barycenter of the nacelle. A constant diameter and thickness is assigned to each element. The rotor and the aerodynamics have not been included in the model due to its complexity, and the nacelle and its internal components are represented by a concentrated mass at the top of the structure, with no dynamic interaction considered. Such mass is added in the global mass matrix at the translational degree of freedom at the top of the tower.

The base system has been modeled as in Fig. 3, that is by a rotational spring k_{spring} and a Maxwell element (representing the MR dampers) working in parallel. The value for k_{spring} (4.82e8 Nm/rad) has been easily derived known the stiffness of the two linear springs and their distance from the center of rotation (hinge).

The Maxwell element, as known, consists of a spring $k_{Maxwell}$ and a linear viscous damper $c_{Maxwell}$ in series. The controllable part of this device is represented by the constant $c_{Maxwell}$, while $k_{Maxwell}$ has been simply assumed high enough (1.0e11 Nm/rad) so as to behave like a rigid link. Two different values of $c_{Maxwell}$ (c_{on}, c_{off}) have been determined so as to reproduce the dissipative capability of MR dampers respectively in the ON and OFF states. These two opposite configurations of the MR dampers are assumed to be those corresponding to two feeding currents i=$i_{\min}$ and i=$i_{\max}$ considered for the MR dampers. Suitable numerical models for such kind of devices are described in [9]. The values of c_{on}=1e12 Nms/rad (i=$i_{\max}$=1 A) and c_{off}=2e8 Nms/rad (i=$i_{\min}$=0) have been extrapolated on the basis of preliminary experimental tests carried out on a scaled structural model of the examined case study real turbine tower [8].

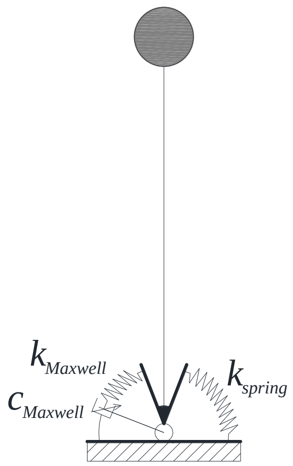

Figure 3 - Representation of the base restraint within the FE model of the SA controlled structure.

A customized integration procedure has been formulated for the analyses: the structure is analyzed by using the Newmark method, while the Maxwell support is analyzed separately feeding a force to the tower. The integration procedure is based on forward and backward differences, which yield to the base bending moment. In order to simulate the time delay of the real mechanical response of the MR dampers, each ON/OFF and OFF/ON switch is imposed to occur not instantaneously but in ten milliseconds by following a linear law.

3.3 Numerical investigation

A number of 152 numerical tests have been performed with reference to the above FEM model in SA configuration. This corresponds to the total number of different combinations of stress (σ_{lim}) and displacement (x_{lim}) limits that have been tested, chosen within the ranges [10, 80] MPa and [50, 1200] mm with a step of, respectively, 10 MPa and 50 mm, except for the step of 100 mm from 700 mm to 1200 mm. In order to compare the effectiveness of the SA control strategy for each of the above settings of the controller, and to single out the optimal calibration of the latter, the structural response has been summarized by computing the following defined performance indices:

- ratio of maximum bending stress $\sigma_{\max}$ to limit value σ_{lim} assumed to calibrate the controller ($\sigma_{\max}$ / σ_{lim});
- ratio of maximum bending stress in SA to fixed base (FB) conditions ($\sigma_{\max}$ / $\sigma_{\max,FB}$);
- ratio of maximum top displacement in SA to FB conditions ($x_{\max}$ / $x_{\max,FB}$).

Then, to better interpret the results, the following two additional information have been considered:

- total amount of time in which the MR damper has been switched off by the controller (t_{off});
- total number of switches (on→off and vice versa) commanded to the variable device (n_{sw}).

The ratio $\sigma_{\max}$ / σ_{lim} is assumed so as to check if and how the controller has been able to limit the bending stress to the desired value σ_{lim}, while the ratio $x_{\max}$ / x_{lim} has not been assumed as parameter for comparison because it is not significant to the same extent given that x_{lim} has a reduced impact on the controller operation. The indices $\sigma_{\max}$ / $\sigma_{\max,FB}$ and $x_{\max}$ / $x_{\max,FB}$ express the effectiveness of the controller in reducing the structural response with respect to the FB conditions. Values less than one are desired, in fact they reflect the main purpose of the control strategy. The indices t_{off} and n_{sw} give a quantitative idea about the activity of the MR damper during each test. When the smart device is set to "ON", it is not very far from acting as a rigid link. Therefore, the above t_{off} gives also a measure of the overall duration of the dissipation phase.

4 DISCUSSION OF THE RESULTS

The constrained optimization of the controller is performed according to the condition in Eq. (2), that is, aiming to achieve the highest reduction of the base stress and, at the same time, a top displacement no higher than that in uncontrolled FB condition.

$$\min\left(\sigma_{\max}/\sigma_{\max,FB}\right) \quad \text{subject to} \quad x_{\max}/x_{\max,FB} \leq 1 \tag{2}$$

Analyzing diagrams (a) to (d) in Fig. 4, it is possible to state that the SA control of the case study wind turbine is almost always beneficial in terms of reduction of base stress with respect to the fixed base scheme. Considered the whole set of examined cases, the maximum base stress reduction results to be around 73%, and corresponds to the case (σ_{lim}, x_{lim})=(10 MPa, 900 mm). The maximum top displacement reduction is about 43%, for (σ_{lim}, x_{lim})=(20 MPa, 50 mm). The worst case, i.e. that corresponding to the maximum amplification of x (+30%) with respect to the FB case is (σ_{lim}, x_{lim})=(30 MPa, 1200 mm).

A higher number of operations of the SA controller can be expected for smaller values of σ_{lim}, as shown in Fig. 4(f). Then, Fig. 4(e) highlights that maximum base stress $\sigma_{\max}$ is practically always included in the interval [σ_{lim}, 2σ_{lim}], with the exception of those cases where both very small values are fixed both for σ_{lim} and x_{lim}.

The response $\sigma_{\max}$ is roughly monotonic with varying the assumed value for σ_{lim}: the smaller the assumed value for σ_{lim}, the smaller the recorded value of $\sigma_{\max}$, the value of the latter also being dependent on the value set for x_{lim} (Fig. 4(a)). The response $x_{\max}$ doesn't show the same trend (Fig. 4(b)), because the response fluctuates around the value (1170 mm) registered for the FB case.

It results that, when values of σ_{lim} greater than 60 MPa are adopted (i.e. roughly greater than 0.75$\sigma_{\text{max,FB}}$), there is no chance to reduce displacements in respect to the FB case. The reason is related to the fact that in such cases the SA operations are really limited, as from Fig. 4(f) clearly emerges. Therefore, the dissipation phases are concentrated in much small intervals of time, not effective in reducing significantly the response in displacement. Vice versa, when smaller values of σ_{lim} are used (i.e. less than 60 MPa), the reduction or amplification of $x_{\max}$ in respect to $x_{\text{max,FB}}$ also depends on the assumed value for x_{lim}. It seems that selecting values for x_{lim} less than 0.5$x_{\text{max,FB}}$ leads always to good results in terms of displacement response.

According to the criterion defined in the condition above, the optimal configuration of the control algorithm corresponds to the case (σ_{lim}, x_{lim})=(10 MPa, 900 mm) since it leads to the maximum response reduction (about 73%) in base stress, and also to a reduction (about 34%) of displacement in respect to the FB case.

Therefore, preliminary conclusions about a possible way to optimally calibrate the controller could be drawn suggesting to assume, for σ_{lim} and x_{lim}, values respectively around 0.1÷0.12$\sigma_{\text{max,FB}}$ and 0.8÷1.00$x_{\text{max,FB}}$. Moderately low values of σ_{lim} (30-50% of $\sigma_{\text{max,FB}}$) leaded to increased top displacements, even higher than the reference value $x_{\text{max,FB}}$. A trend reversal for values of σ_{lim} even more smaller (10-20% of $\sigma_{\text{max,FB}}$) has been registered, leading them to significant reduction of both base stress and top displacement, as said above, due to the higher number of operations of the controller and, consequently, to the sharp increase of dissipated energy due to the larger rocking of the base.

In order to directly evaluate the influence of the P-Δ effect on the structural response, gravity load has been also considered during the non-linear analyses, without causing a significant increase to computational time. Fig. 5 shows the influence of the P-Δ effect in the FB condition: if it is neglected, the numerical analysis is not able to capture an amplification up to 9% in top displacements and up to 14% in base stresses. But, this influence on top displacements and base stresses is contrasted by the operation of the SA controller, as clearly made in evidence by Fig. 6:

the introduction of the P-Δ effect in the non-linear analyses produces an amplification of only 1% in top displacements while even a reduction of 6% is detected in base stresses. Top displacements of Fig. 6 show a residual displacement due to the intrinsic operation decided by the adopted control algorithm. This behavior could represent a problem for longer wind load cases.

Therefore, the above results cannot be directly generalized, since clearly dependent on the specific wind load case and turbine model assumed for the analyses. Future further research about this topic will have to consider a larger set of wind load cases, to understand if and how the optimal calibration of the control algorithm depends on the characteristics of the external action.

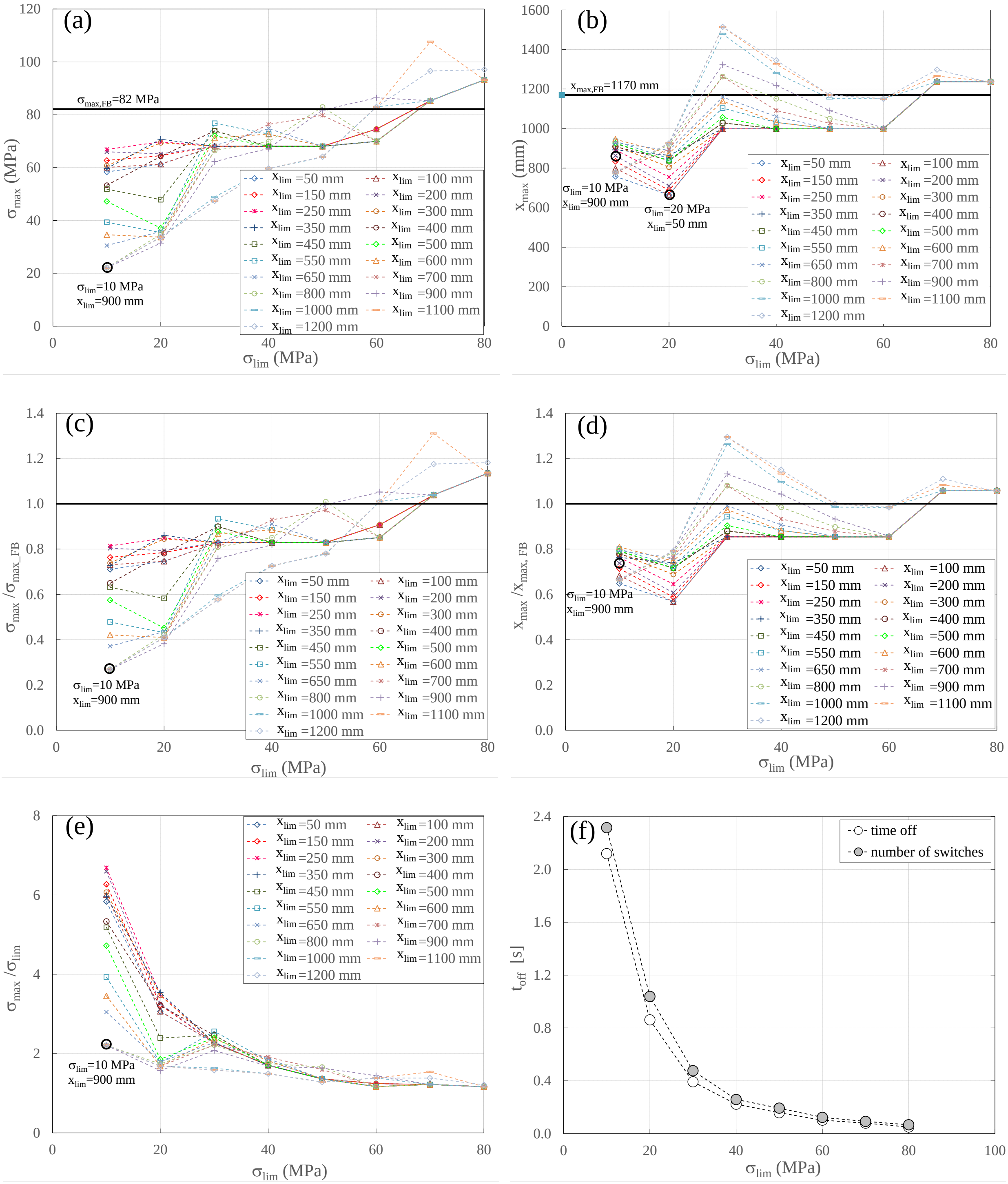

Figure 4 - Performance indices for the 100 configurations of the SA controller.

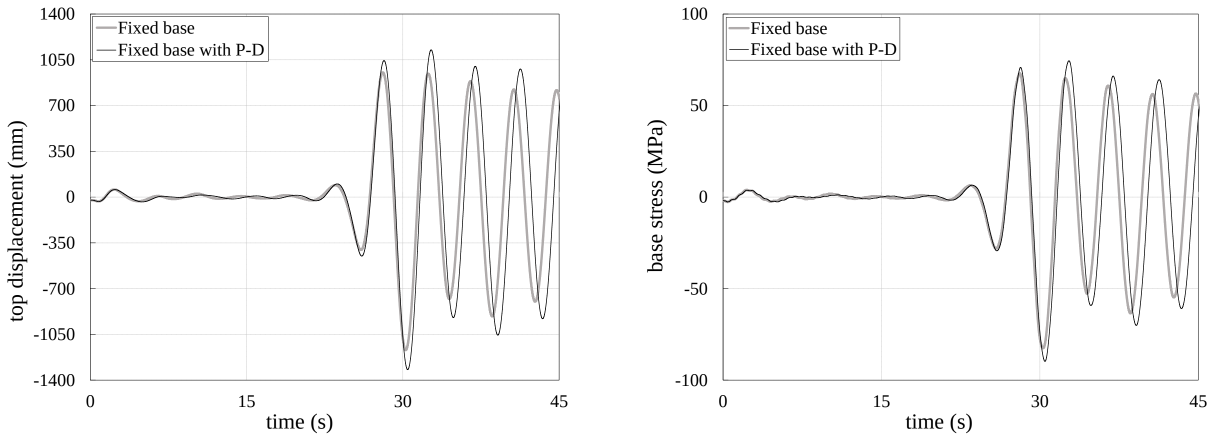

Figure 5 - Base stress and top displacement response time-histories: comparison relative to the FB configuration, with vs. without P-Δ effect

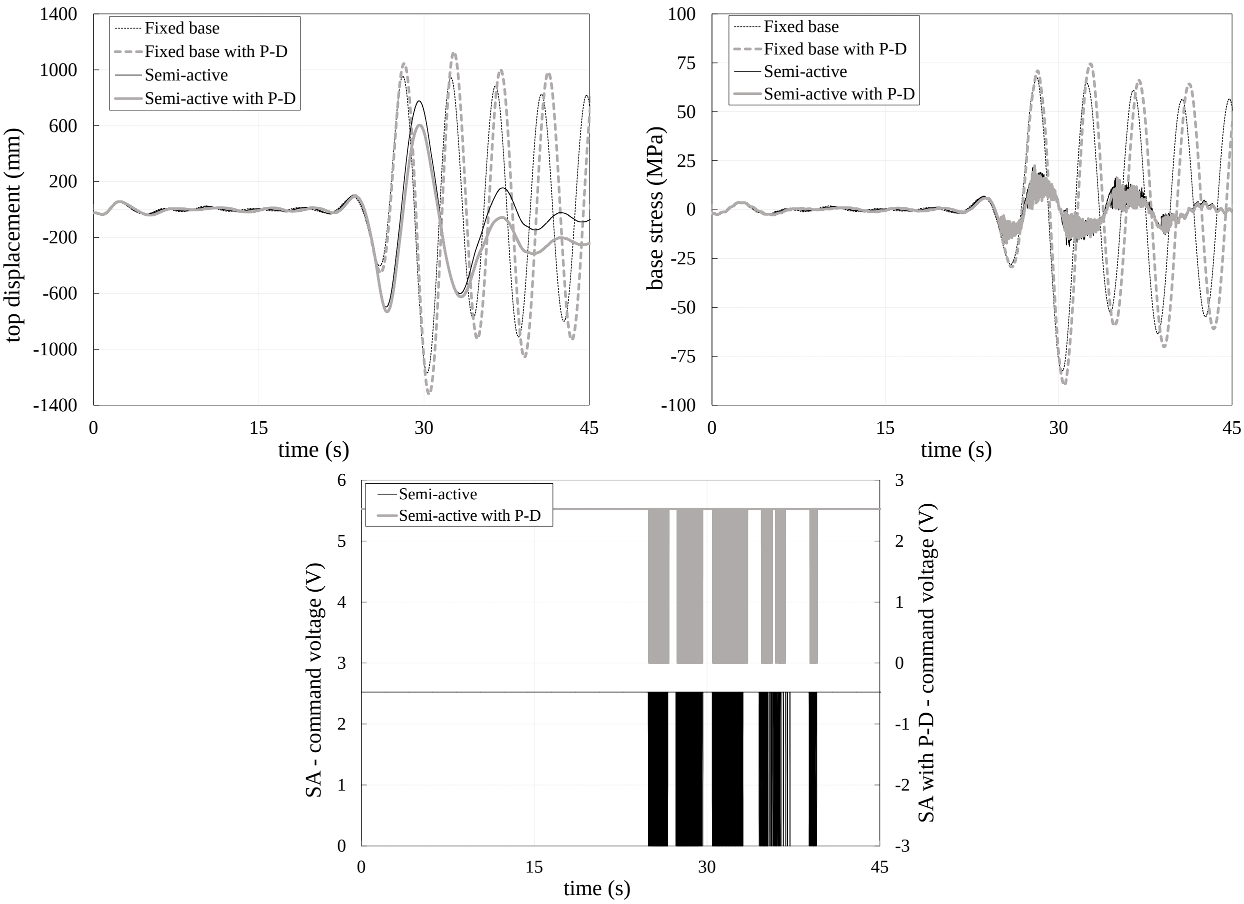

Figure 6 - Base stress, top displacement and command voltage time-histories: comparison relative to the selected case (σ_{lim}, x_{lim})=(10 MPa, 900 mm), with vs. without P-Δ effect

5 CONCLUSIONS

The effectiveness of a smart base restraint for wind turbines to reduce structural demand under extreme wind loads has been investigated. The technique is based on the dissipation of energy associated to the rocking of the base, where variable dampers driven by a specific control algorithm are installed. This has been explored with reference to a commercial 3 MW wind turbine, 102.5 m tall and a realistic wind load simulating the effect of an extreme operating gust. Several configurations of the controller have been assessed in terms of reduction of demand of base stress and of top displacement. The main conclusions, some surprising, can be summarized as follows:

- relaxing several times the restraint at the base of the tower, while leading to the reduction of the stresses at the base, does not necessarily imply an increase of the top displacement with respect to the fixed base condition;
- suitably calibrating the control algorithm, it is even possible to achieve at the same time (small) reductions of top displacement and (significant) reductions of bending stress at the base;
- while the p-delta effect results to be detrimental – as expected – for a conventional, fixed base structural scheme, it produces negligible effects (in some cases even beneficial) when the SA control scheme is adopted.

Future developments of this idea should be addressed to:

- the involvement of more wind loads, different one each other for intensity, duration, frequency content, so as to understand if an unique optimal configuration of the controller can be defined for all of them;
- understand whether and how to reduce the residual top displacement due to the possible incremental base rotation that may happen during a wind load history, especially when it is long lasting. In other words, a possible way to give a recentering action (or actions) at the end of (or periodically during) the severe load history should be evaluated.

REFERENCES

[1] Chen, J. & Georgakis, C.T. Tuned rolling-ball dampers for vibration control in wind turbines, *Journal of Sound and Vibration*, 332, 5271-5282, 2013, dx.doi.org/10.1016/j.jsv.2013.05.019.

[2] Chen, J. & Georgakis, C.T. Spherical tuned liquid damper for vibration control in wind turbines, *Journal of Vibration and Control*, 2015; **21**(10), 1875-1885, doi: 10.1177/1077546313495911.

[3] Karimi, H.R., Zapateiro, M. & Luo, N. Semiactive vibration control of offshore wind turbine towers with tuned liquid column dampers using H∞ output feedback control, *Proceedings of the IEEE International Conference on Control Applications*, Yokohama, Japan, 2010.

[4] Luo, N., Bottasso, C.L., Karimi, H.R. & Zapateiro, M. Semiactive control for floating offshore wind turbines subject to aero-hydro dynamic loads, *Proceedings of the International Conference on Renewable Energies and Power Quality*, Las Palmas de Gran Canaria, Spain, 2011.

[5] Lackner, M. & Rotea, M. Structural control of floating wind turbines, *Mechatronics,* 2011; **21**, 704-719, doi:10.1016/j.mechatronics.2010.11.007.

[6] Kirkegaard, P.H., Nielsen, S.R.K., Poulsen, B.L., Andersen, J., Pedersen, L.H. & Pedersen, B.J. Semi-active vibration control of a wind turbine tower using an MR damper, *H. Grundmann, G.I. Schuëller, Rotterdam: Balkema Publishers, A.A. / Taylor & Francis The Netherlands,* 1575-1580, 2002.

[7] Caterino, N., Georgakis, C.T., Trinchillo, F. & Occhiuzzi, A. A semi-active control system for wind turbines, *In: N. Luo, Y. Vidal, L. Acho, Wind Turbine Control and Monitoring, Springer International Publishing*, 375-407, *Advances in Industrial Control*, 2014, doi: 10.1007/978-3-319-08413-8_13.

[8] Caterino, N. Semi-active control of a wind turbine via magnetorheological dampers, *Journal of Sound and Vibration*, 2015; **345**, 1-17, doi:10.1016/j.jsv.2015.01.022.

[9] Caterino, N., Spizzuoco, M. & Occhiuzzi, A. Understanding and modelling the physical behaviour of magnetorheological dampers for seismic structural control, *Smart Material and Structures*, 2011; **20**(6), doi:10.1088/0964-1726/20/6/065013.