Structural Control of a Wind Turbine Accounting for Second Order Effects

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Abstract. The negative impact of the use of fossil fuels on the environment has lead to a boom in the production of wind turbines. The progressively increasing turbines' height, decided to take advan-tage of the smoother winds at higher altitude, has led to an increased demand to control tower forces. The proposed work is focused on the application of a semi-active (SA) control system 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. 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 considered as a case study. Several numerical simulations have been performed with reference to two extreme loads, different one each other for intensity, duration, frequency content, so as to understand if a unique optimal configuration of the controller can be defined for both of them. The proposed study is also focused on understanding 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.

1. Introduction

Wind turbine manufacturers have become ever more interested in methods for limiting tower base moments determined by the increasing height of wind turbines. The first reason is that the tower diameters at the base are increasing beyond the point where they can be fabricated off-site, so that construction costs and complexity are significantly increasing. The second reason is that the tower diameters and associated base moments of newer wind turbines are significantly higher than those of existing wind turbines. 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 combined with emergency shut-down procedures. 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.
Karimi et al. [1] and Luo et al. [2] proposed 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 [3] investigate the effectiveness of an optimal passive TMD and of a hybrid mass damper 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. [4] 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 [5] [6]. The controller has to be designed 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. 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 new base restraint is applied to high-rise wind turbine towers, in order to reduce their wind induced structural demand. It consists in a semi-active rocking system, exploiting controllable fluid based devices, as schematically shown in figure 1: the uncontrolled wind turbine is fully restrained at the base and can be simulated by a single degree of freedom dynamic system (figure 1(a)) having top mass $m$, stiffness $k_T$ and inherent damping $c_T$; figure 1(b) shows the proposed smart base restraint, whose stiffness can be instantaneously be modified during the motion, by mounting at the base of the tower a smooth hinge, a rotational spring (of stiffness $k_\phi$) and a rotational variable damper whose damping coefficient $c_\phi$ can be driven in real time by a proper control logic; the proposed idea can be more simply achieved by mounting two vertical linear springs ($k_s$) placed at a certain distance ($l_s$) from the hinge and two vertical SA magnetorheological (MR) dampers ($c_d$) at a distance $l_d$ from the central hinge (figure 1(c)). The base control system is able to produce a real time modification of the system’s stiffness by varying the MR dampers’ mechanical properties according to a given control algorithm. A simple physical approach was formulated by the authors [5] [6] to reduce base stress, by restraining the increase of top displacements within certain limits to control second order effects: the objective was to achieve a trade-off between the contradictory purposes to limit the base stress $\sigma_{\text{lim}}$ and the top displacement $x_{\text{lim}}$. 
Figure 1: Basic idea of SA rocking control of a wind turbine

In other words, a bang-bang controller keeps ‘stiffer’ the base restraint (switches to an ON state by commanding a maximum current $i = i_{\text{max}}$ to the dampers) until the stress doesn’t exceed a limit value $\sigma_{\text{lim}}$. Conversely, the controller ‘relaxes’ the base restraint (switches to an OFF state by delivering a minimum current $i = i_{\text{min}}$ to the dampers) when the limit stress is overpassed and the displacement falls within the limit of acceptability $x_{\text{lim}}$, so that the structure is able to convert its potential energy into kinetic energy. The following instructions are applied:

\begin{align}
\text{a) } & \ 	ext{if } \sigma(t) < \sigma_{\text{lim}} & \Rightarrow i(t) = i_{\text{max}} \\
\text{b) } & \ 	ext{if } \sigma(t) \geq \sigma_{\text{lim}} \text{ and } x(t) < x_{\text{lim}} & \Rightarrow i(t) = 0 \\
\text{c) } & \ 	ext{if } \sigma(t) \geq \sigma_{\text{lim}} \text{ and } x(t) \geq x_{\text{lim}} \text{ and } x(t) \cdot \dot{x}(t) > 0 & \Rightarrow i(t) = i_{\text{max}} \\
\text{d) } & \ 	ext{if } \sigma(t) \geq \sigma_{\text{lim}} \text{ and } x(t) \geq x_{\text{lim}} \text{ and } x(t) \cdot \dot{x}(t) \leq 0 & \Rightarrow i(t) = 0
\end{align}

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 $t$. When both stress and displacement are beyond their threshold values, the controller switches the dampers to an ON state if the displacement is going towards a larger value (i.e., positive velocity), so trying to damp or invert the displacement’s trend; otherwise it switches the MR devices to an OFF state to make them collaborating to both stress and displacement reduction. 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.

3. Calibration of control parameters for a real wind turbine

The optimal choice of the parameters $\sigma_{\text{lim}}$ and $x_{\text{lim}}$ involved in the control algorithm requires the following calibration procedure: as first step, a finite element model of the examined structure is developed to simulate both fixed base (FB), passive (PA) and SA controlled configurations; as second step, the structural response in the FB case is computed under the considered extreme loads; then, a wide number of SA numerical simulations is designed and performed for each wind load. Finally, the application of a constrained optimization approach in the analysis of the results allows to single out an optimal configuration of the controller able to achieve a satisfactorily large reduction of base stress under the assumed inputs, while not producing increasing of top displacement with respect to the FB cases. This procedure is showed in the following for a specific case study.
3.1. Case study: a real 3MW wind turbine

A real 3 MW wind turbine is the case study structure: 102.4 m tall, a variable hollow circular cross section having an external diameter variable from 2.30 m (top) to 4.15 m (bottom), and a thickness 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 supported in the middle by a cylindrical steel hinge, while on both sides one cylindrical spring of stiffness 1417 kN/m and one SA MR damper are installed. The elements of the assemblies “elastic spring + SA MR damper”, placed in parallel at the base of the tower, just represent the smart base restraint proposed by the authors to control the dynamic behaviour of the structure. Two load cases have been considered in the following as reference wind actions: 1. an extreme operating gust (EOG), i.e. a sharp increase, then decrease in wind speed within a short period of time; 2. an high velocity wind buffeting, i.e. a load case (called “parking”, PRK) that typically concerns a wind turbine when “parked” (with a controlled shut-down) due to the high-velocity wind. Chen and Georgakis [7] defined the equivalent base acceleration time histories (figure 2), that are the base inputs that would provide the same top mass response of the real fixed base structure subjected to the wind actions. They are significantly different one each other for duration and frequency content.

![Figure 2: Equivalent base accelerations corresponding to two wind load cases: (a) extreme operating gust (EOG) and (b) parking (PRK)]](image)

3.2. Numerical model

The dynamic behaviour of the case study real structure has been simulated by a finite element model developed in Matlab environment. It consists in 37 elements: 36 of them simulate the tower with variable hollow circular cross section, while the 37th element (at the top) is more rigid (a double second moment of inertia is assigned) because it represents the connection of the tower’s top to the barycenter of the nacelle. Each element has constant diameter and thickness. The rotor and the aerodynamics have not been taken into account due to its complexity, so that the nacelle and its internal components are represented by a concentrated mass at the top of the structure, without considering any interaction. Such mass is added in the global mass matrix at the translational degree of freedom at the top. The base system has been modelled (see figure 3) by a rotational spring $k_{spring}$ and a Maxwell element (representing the MR dampers) connected in parallel. The value for $k_{spring}$ (4.82e8 Nm/rad) has been easily derived by the stiffness of the two linear springs located at a known distance from the center of rotation (hinge).

The Maxwell element, as known, consists of a spring $k_{Maxwell}$ and a linear viscous damper $c_{Maxwell}$ connected in series: the controllable part of this device is the parameter $c_{Maxwell}$, 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 assumed so as to reproduce the dissipative capability of MR dampers respectively in the ON and OFF configurations: the values of $c_{on}=1e12$ Nms/rad (corresponding to the feeding current $i=i_{max}=1$ A) and $c_{off}=2e8$ Nms/rad (corresponding to a zero feeding current - $i=i_{min}=0$)
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 [6].

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

The integration procedure for the numerical simulations has been formulated, by analysing the structure through the Newmark method, and by considering the Maxwell support separately feeding a force to the tower. The integration procedure is based on forward and backward differences, which yield to the base bending moment. The time delay of the real mechanical response of the MR dampers has been simulated by imposing that each ON/OFF and OFF/ON switch occurs not instantaneously but in ten milliseconds according a linear law.

In order to directly evaluate the P-Δ effect on the structural response, the gravity load has been considered during the numerical analyses. Figures 4 and 5 show the influence of the P-Δ effect in the FB condition: if it is neglected, the numerical analysis under EOG input is not able to capture an amplification up to 13% in top displacements and up to 9% in base stresses, and the numerical analysis under PRK input doesn’t see a top displacements’ amplification up to 43% and a base stresses’ amplification up to 38%.

Figure 4: Base stress and top displacement response under EOG: comparison relative to the FB configuration, with vs. without P-Δ effect
3.3. Numerical investigation
A number of 48 numerical tests have been performed on the above FEM model in SA configuration, for each of the assumed extreme loads. This number corresponds to the different combinations of stress ($\sigma_{\text{lim}}$) and displacement ($x_{\text{lim}}$) limits that have been tested, belonging to the arrays [5, 10, 20, 40, 60, 90] MPa and [100, 200, 300, 400, 600, 900, 1200, 1400] mm. All the numerical tests have been run either including the P-\Delta effect or neglecting it.

Figure 5: Base stress and top displacement response under PRK: comparison relative to the FB configuration, with vs. without P-\Delta effect.

In order to compare the effectiveness of the SA control strategy for each of the above couple ($\sigma_{\text{lim}}$, $x_{\text{lim}}$) of controller’s parameters, and to single out the optimal calibration of the latter, the structural response has been summarized according to the following defined performance indices:

- ratio of maximum bending stress in SA to fixed base (FB) conditions ($\sigma_{\text{max}} / \sigma_{\text{max,FB}}$);
- ratio of maximum top displacement in SA to FB conditions ($x_{\text{max}} / x_{\text{max,FB}}$);
- Then, the following two additional information have been computed to better interpret the results:
  - total amount of time in which the MR damper has been switched off by the controller ($t_{\text{off}}$);
  - total number of switches (on\rightarrow off and vice versa) commanded to the variable device ($n_{\text{sw}}$).

The indices $\sigma_{\text{max}} / \sigma_{\text{max,FB}}$ and $x_{\text{max}} / x_{\text{max,FB}}$ make in evidence the effectiveness of the controller in reducing the structural response with respect to the FB conditions: values less than one are desired, as they reflect the main purpose of the control strategy. The ratios $\sigma_{\text{max}} / \sigma_{\text{lim}}$ and $x_{\text{max}} / x_{\text{lim}}$ are considered so as to check if and how the controller has been able to limit the bending stress to the desired value $\sigma_{\text{lim}}$ and the top displacement within the maximum top displacement in FB condition $x_{\text{max,FB}}$. The indices $t_{\text{off}}$ and $n_{\text{sw}}$ give a quantitative idea about the activity of the MR damper during each test: when the smart device is set to “ON”, it acts nearly as a rigid link, so that the above $t_{\text{off}}$ gives also a measure of the overall duration of the dissipation phase.

4. Discussion of the results
On the base of the physical meaning of the control logic, it is expected that a moderate reduction of base stress is achievable when a large value of $\sigma_{\text{lim}}$ is adopted (i.e. little lower than the maximum value of base stress in FB condition), while top displacement demand may increase significantly. This result is due to a limited number of SA operations, so that the dissipation phases are concentrated in small intervals of time, not effective in reducing significantly the response. Vice versa, the system benefits from a greater dissipation of energy when smaller values of $\sigma_{\text{lim}}$ are used, and may behave better from both base stress and top displacement points of view, as a function of the assumed value for $x_{\text{lim}}$. 
The constrained optimization of the controller is expressed by the condition in eq. (2), consisting in the achievement of the highest reduction of base stress and, at the same time, a top displacement no higher than that in uncontrolled FB condition.

\[
\min \left( \frac{\sigma_{\max}}{\sigma_{\max,FB}} \right) \quad \text{subject to} \quad \frac{x_{\max}}{x_{\max,FB}} \leq 1
\]

According to the criterion defined in eq. (2), the numerical investigation carried out with the inclusion of the P-\(\Delta\) effect has led to the following issues:

- The optimal configuration of the control algorithm corresponds to the case \((\sigma_{\text{lim}}, x_{\text{lim}}) = (10 \text{ MPa}, 900 \text{ mm})\) when the case study structure is subjected to a short extreme load like EOG; the latter provides the maximum response reduction (about 75%) in base stress, and also a reduction (about 45%) of displacement in respect to the FB case.

- When the studied wind turbine is subjected to a long extreme load as PRK, the optimal configuration of the controller corresponds to the case \((\sigma_{\text{lim}}, x_{\text{lim}}) = (10 \text{ MPa}, 400 \text{ mm})\), by determining the maximum response reduction of 81% in base stress and a significant reduction of 59% in top displacement.

Therefore, a possible way to optimally calibrate the controller consists in assuming for \(\sigma_{\text{lim}}\) and \(x_{\text{lim}}\) values respectively around 0.1\(\sigma_{\max,FB}\) and 0.7\(x_{\max,FB}\), when the applied input is a short extreme operating gust. Whereas a long high velocity wind buffeting is acting, an optimal calibration of the controller corresponds to assign to \(\sigma_{\text{lim}}\) and \(x_{\text{lim}}\) values respectively around 0.1\(\sigma_{\max,FB}\) and 0.3\(x_{\max,FB}\).

The comparisons of the numerical results obtained by including or not the P-\(\Delta\) effect have demonstrated that for short extreme loads, as EOG, the influence of the above effect on top displacements and base stresses is contrasted by the operation of the SA controller: as shown in figure 6, the introduction of the P-\(\Delta\) effect in the non-linear analysis performed with the above optimal configuration \((\sigma_{\text{lim}}, x_{\text{lim}}) = (10 \text{ MPa}, 900 \text{ mm})\) produces an amplification of only 2% in base stresses while even a reduction of 6% is detected in top displacements. Top displacements in figure 6 show a residual displacement due to the intrinsic operation decided by the adopted control algorithm: when the base restraint has a significant rotation at the instant of a switch ON commanded to the MR dampers, the structure accumulates a residual displacement that should be recovered by the elastic springs during the duration of the input. This behavior is of negligible importance in case of short loads but becomes a problem for longer wind load cases like PRK. Figure 7 shows the dynamic response of the case-study structure under the PRK load case, when the configuration \((\sigma_{\text{lim}}, x_{\text{lim}}) = (10 \text{ MPa}, 900 \text{ mm})\) is assigned to the control algorithm. When the strongest input phase occurs in the time interval 80÷120 s, with many narrow spikes and the highest one at 90 s, the base rotations are large and the elastic springs are not able to counter them. That produces a residual and increasing top displacement.

But, under an extreme input as PRK, the influence of the P-\(\Delta\) effect succeeds in being quite contrasted by the SA operation only when low values of both \(\sigma_{\text{lim}}\) and \(x_{\text{lim}}\) are assumed for the controller. Therefore, in this perspective, the parameter \(x_{\text{lim}}\) has demonstrated to be a significant parameter in case of long wind inputs, whereas it has a reduced impact on the controller operation under a short wind load: when a long extreme load is acting, the parameter \(x_{\text{lim}}\) has to be low enough to switch ON and OFF the MR damper more frequently for very short time intervals, in order to counteract the occurring and accumulating of large rotations. Figure 8 shows that the introduction of the P-\(\Delta\) effect in the non-linear analysis performed with the optimal configuration \((\sigma_{\text{lim}}, x_{\text{lim}}) = (10 \text{ MPa}, 400 \text{ mm})\) produces an amplification of only 5% in top displacements while even a reduction of 8% is detected in base stresses: this happens because 10 MPa and 400 mm are significantly low values to contrast the influence of the P-\(\Delta\) effect.
Figure 6: Base stress, top displacement and command voltage time-histories under EOG: comparison relative to the selected case ($\sigma_{lim}, x_{lim}$)=(10 MPa, 900 mm), with vs. without P-\Delta effect.
Figure 7: Base stress, top displacement, command voltage and base rotation response time-histories: comparison of the case (σ_{lim}, x_{lim})=(10 MPa, 900 mm) relative to the FB configuration, with vs. without P-Δ effect.
Figure 8: Base stress, top displacement and command voltage time-histories under PRK: comparison relative to the selected case ($\sigma_{lim}$, $x_{lim}$)=(10 MPa, 400 mm), with vs. without P-$\Delta$ effect

5. Conclusions

The authors have investigated the effectiveness of a smart base restraint for wind turbines in reducing the structural demand under different extreme wind loads. The technique exploits the dissipation of energy associated to the rocking of the base, where semi-active MR dampers are installed. A commercial 3 MW wind turbine, 102.5 m tall, has been investigated, and two realistic wind loads have been assumed, simulating respectively, the effect of an extreme operating gust and of a high velocity wind buffeting. A wide campaign of numerical analyses has been performed by changing the controller’s parameters in properly chosen intervals, and by assessing the structural response in terms of reduction of demand of base stress and of top displacement. The main conclusions are the following:

- The relaxing of the restraint at the base of the tower in selected time intervals, leads to the reduction of the stresses at the base but doesn’t necessarily imply an increase of the top displacement with respect to the fixed base condition.
- A proper calibration of the control algorithm is able to produce at the same time (small) reductions of top displacement and (significant) reductions of bending stress at the base.
- While the p-delta effect is detrimental for a conventional fixed base structural scheme, it produces negligible effects (in some cases even beneficial) when the SA control scheme is adopted to control a turbine under a short extreme wind load.
The p-delta effect can produce important effects when the SA control scheme is adopted to control a turbine under a long lasting extreme wind load: only when the controller is perfectly calibrated, it is able to counteract the residual top displacement due to the incremental base rotation.

Future developments of this idea should be addressed to the possible way to give a recentering action (or actions) to the system, at the end of (or periodically during) a severe load history. The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

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