ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering

A dissipative rocking system to mitigate the structural demand to wind turbine towers against severe wind loads

E. Sorge [1], N. Caterino [1,2], C. Demartino [3], C.T. Georgakis [4]

[1]*Department of Engineering, University of Naples Parthenope, Napoli, Italy,*
ettore.sorge@studenti.uniparthenope.it
[2]*Institute of Technologies for Construction, CNR, San G. Milanese, Milan, Italy*
[3]*University of Roma Tre, Roma, Italy*
[4]*Department of Engineering, Aarhus University, Aarhus, Denmark*

SUMMARY:
The rise in demand for wind energy has prompted the deployment of progressively taller and more sizable horizontal axis wind turbines (HAWTs), which in turn necessitates the mitigation of severe stress demand on both the tower and the foundation. In this work, the performance of a passive control device based on the use of a rotational friction damper (RFD), installed at the base of the tower, is tested with the aim of reducing the bending moment demand. To test the device, an extreme load case purposely generated for this research is applied to a case-study HAWT. Such a load case is equivalent to an extreme wind applied when the turbine is in an operative scenario. The wind and aerodynamic model of the tower were generated by making use of a recent up-to-date release of the Qblade software, while the structural model was developed in Simulink. The device is calibrated with reference to the NREL 5MW on-shore wind turbine. The results show that the proposed technique is able about 20% reduce the bending stress at the base of the tower against the above reference severe wind load, compared to the bending demand for a fixed base tower configuration.

Keywords: Rotational friction damper, wind turbine, vibration control

1. INTRODUCTION

The dependence of power generation on fossil fuels is no longer acceptable, so the transition into activities using clean energy has become a real urgency. In the last three years, the worldwide wind power capacity has grown by approximately 12% (837 GW) according to a recent report from the Global Wind Energy Council (2022). It has allowed reducing around 1.2 billion tons of CO2 per year. Because of that, more efforts have been developed in this direction, as reflected in the market outlook for the global wind industry. Furthermore, a further increase of about 60% is expected in this sector for the incoming five years. The investments are driven by two distinct needs. The first one is to ensure increasing levels of productivity through newly installed turbines with higher and higher wind towers. This often involves technological issues, such as: construction, transport, and installation of huge steel components to realize large-diameter towers able to withstand to so severe solicitations. The same holds for the foundation. The second one, which has been growing in recent years, is the renewal of existing wind farms with the aim of maximizing energy production and improving the efficiency of the system. Actually, the progressive aging (tens of years) of wind turbines causes a reduction in the production capacity, mainly due to the deterioration of the mechanical and/or electronic components. From a practical standpoint, repowering can prove to be a favorable alternative to the extensive decommissioning and subsequent reconstruction of a wind farm. However, this remains particularly true if repowering efforts incorporate pioneering solutions designed to optimize the overall benefits. In this regard, the application of structural control devices capable of effectively mitigating structural vibrations in high wind towers may prove to be a valuable tool. Many solutions in literature focuses on the energy dissipation to damp vibrations at the nacelle (Feng, et al., 2023; Jiang and Xing, 2022). Only a few research are addressed tower vibration control and the mitigation of wind-induced structural demand on tower and foundation. Such approaches may be very effective in reducing the structural dimensions needed for such elements, both for new installation and for repowering cases (in the latter case the stress reduction at foundation could make it possible to reuse it also for the new plant).

Among them highlights that developed by Di Paolo et al. (2021), which involves a passive control device based on the use of a Rotational Friction Damper (RFD) (Mualla and Belev, 2002). The present work is an evolution of that of 2021. Further analyses have been performed to investigate the robustness of the control strategy. Apart from that, the study focuses on the optimization of the structural model and proposes a more in-depth wind generation approach, carried out through recent dedicated software. The performance of the control system has been explored against extreme wind conditions in an operative scenario.

2. DEVICE APPLIED TO TOWER

The RFD, typically implemented for seismic protection of frame structures, is being investigated for stress reduction purposes in onshore wind turbines. The authors' conceptualization of the tower-device configuration is depicted in three-dimensional form (Fig. 1a) and involves the installation of a series of vertically aligned springs situated circumferentially at the interface connecting the tower's base and its foundation. The base of the tower is articulated through a ball friction joint (RDF). The base rocking is contrasted by the springs (adding stiffness) and the friction device (mitigating the local structural demand to the tower by dissipating energy). For simplicity, at this stage the evaluation of the performance of such a system relating it back to the 2D case (Fig. 1b). Such special dissipative constraint of the base must be calibrated to reduce the bending demand as much as possible, compared with the fixed base (FB) condition.

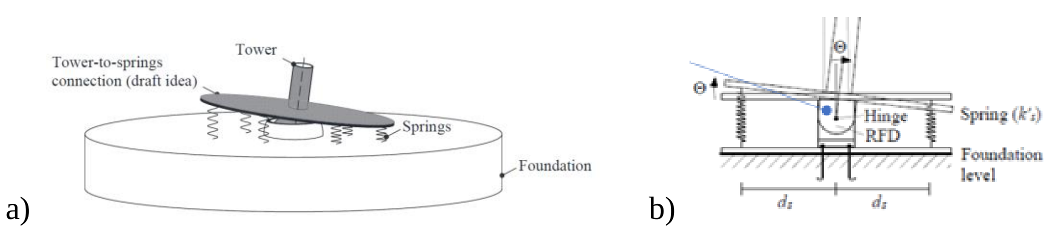

Figure 1. a) Wind turbine 3D equipped with RFD; b) 2D model for the wind turbine equipped with RDF and a rotational spring (Di Paolo et al., 2021)

3. WIND LOAD AND AERODYNAMIC MODEL

The wind and aerodynamic behavior of the turbine including blades, rotor and tower was modelled with the Qblade software (QbladeCE, release 2.0.5.1, Marten, 2020). The wind considered to test the performance of the control system follows the extreme turbulence model (ETM) according to IEC64100-1 (2009), considering a normal wind profile (NWP). The turbulence model was chosen according to the Kaimal spectrum (Kaimal et al., 1972) for IA class of wind turbine. The case-study wind turbine is the benchmark NREL 5 MW (Jonkman et al., 2009), currently adopted as reference structure by most of the scientific community in the field.

The average speed at the hub is set to be v_m=25 m/s, which is the maximum speed at which the tower is still operating before the cut-out. As a first step, the wind grid (Fig. 2a) was generated, whose trend at the hub is described in Fig. 2b. The wind time-history, with a duration of 600 s, was applied to the aerodynamic model once set the rotor parameters (23.47°pitch angle , 12.1 rpm,, etc.). Finally, the thrust and the moment at the hub were obtained and then applied to a FEM structural model (see details in the next section).

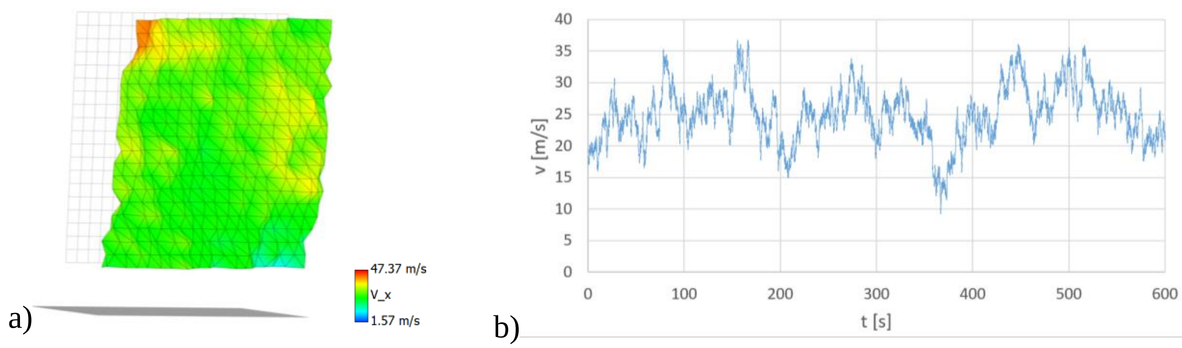

Figure 2. a) Example of windfield on QbladeCE; b) Wind speed at the hub with average speed 25 m/s.

4. STRUCTURAL MODEL AND RESULTS

The dynamic behaviour of the structure has been simulated with a finite element model developed in Matlab/Simulink environments (MATLAB, R2022b). The presented numerical model is characterized by a simplified approach, with a strong emphasis placed on detailing the constraints associated with the tower and the base. Conversely, the blade, hub, and nacelle components have been omitted as additional masses located at the upper portion of the tower and are not explicitly considered as integral structural elements. Non-linear time history analyses have been performed against the wind load defined in Section 3. The analysed were performed by considering the strength of the rotational friction device $M_{fr,y}$ in the range from 0.05 to 0.50 times the $M_{base,FB;max}$ value (i.e. maximum moment at the base of the tower in the "fixed base" configuration) and the rotational stiffness due to the vertical springs k_s from 0.5 to 2.5 times the k_{tower} value (i.e. chord rotational stiffness of the tower). Several possible combinations of values ($M_{fr,y}$, k_s) are then investigated, looking for the couple of values that allows the highest reduction of base bending moment demand. In particular, assuming for $M_{fr,y}$ and k_s respectively ten values belonging to the above-defined ranges, a total of 100 analyses were performed. In all the cases, a reduction of the bending moment demand from the FB to the rotating base (RB) configuration is observed. Fig.3a shows the performance of the 100 pairs of values ($M_{fr,y}$. k_s) examined. The contour lines indicate the location of the points of equal performance in terms of the maximum moment ratio, with the best solution (i.e. the one that gives the greatest moment reduction, about 20%), corresponds to $M_{fr,y}$ =0.1 $M_{base,FB;max}$ and k_s=1.2 k_{tower}. For the last case, the bending moment time-history for both FB and RB responses is shown in Fig. 3b.

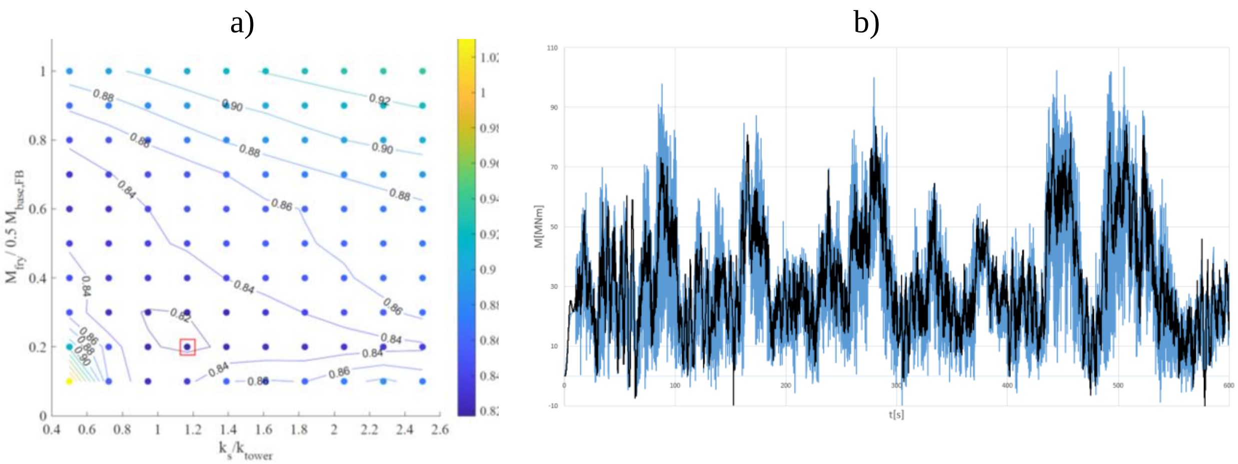

Figure 3. a) Percentage moment reduction for the 100 investigated control system configurations (highlighted in red the best one); b) Bending moment time-history for FB and RB cases for the best configuration.

5. CONCLUSIONS

A novel passive vibration control system designed for a commercial HAWT was subjected to an extreme wind load case generated using Qblade software. The findings demonstrate a noteworthy reduction in moment, estimated to be approximately 20%, in comparison to an uncontrolled wind turbine. The present study serves to further corroborate the efficacy of the approach previously proposed by the authors, with notable improvements observed in both wind load modelling and the selection of the optimal configuration for the control system.

REFERENCES

Marten, D., 2020. QBlade: a modern tool for the aeroelastic simulation of wind turbines.

Di Paolo, M., Nuzzo, I., Caterino, N., & Georgakis, C. T., 2021. A friction-based passive control technique to mitigate wind induced structural demand to wind turbines. Engineering Structures, 232, 111744.

Feng, Z., Huang, Y., Hua, X., Dai, J., and Jing, H. (2023). Vibration-Resistant Performance Study of a Novel Floating Wind Turbine with Double-Rope Mooring System and Stroke-Limited TMD. Journal of Marine Science and Engineering, 11(1), 58.

IEC 61400-1, 2009. International Standards, Wind Turbines - Part 1: Design requirements.

Jiang, Z., and Xing, Y., 2022. Load mitigation method for wind turbines during emergency shutdowns. Renewable Energy, 185, 978-995

Jonkman, J., Butterfield, S., Musial, W. and Scott, G., 2009, Definition of a 5-MW Reference Wind Turbine for Offshore System Development, Office of Energy Efficiency and Renewable Energy: Washington, DC, USA.

Kaimal, J. C., Wyngaard, J. C. J., Izumi, Y., & Coté, O. R., 1972. Spectral characteristics of surface-layer turbulence. Quarterly Journal of the Royal Meteorological Society, 98(417), 563-589.

Mualla H. Belev B., 2002, Performance of steel frames with a new friction damper device under earthquake excitation, Engineering Structures, 24:3, 365–371.

MATLAB version 9.13.0.2049777, 2022 (R2022b) Update 2. Natick, The MathWorks Inc., Massachusetts.

Global Wind Energy Council, 2022, https://gwec.net/wp-content/uploads/2022/04/Annual-Wind-Report-2022_screen_final_April.pdf