Vibration control of a wind turbine with a hybrid mass damper

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Abstract. It is studied the application of structural control in the protection of wind turbines subjected to external loads, such as wind and earthquake, which can compromise the safety and integrity of the structure with excessive vibrations. Structural control can be classified as passive, active, hybrid or semi-active control. The structural control device used is the hybrid mass damper (HMD), which is the combination of a tuned mass damper (TMD) with an active controller. It is a more robust and reliable control when compared only to active and passive dampers. The objective of this research is to numerically analyze the behavior of a dynamically loaded wind turbine and apply a hybrid control system. A comparative study of the performances obtained by different controllers is presented, such as proportional integral derivative (PID) and linear quadratic regulator (LQR). Numerical simulations are performed using the Matlab computational package and its Simulink control toolbox. A wind turbine tower has been analyzed using the technique of reducing tall towers to a single degree of freedom. The results showed that the HMD was efficient in controlling the dynamic response of the tower.

Keywords: hybrid mass damper, tuned mass damper, wind turbine, structural control, excessive vibrations.

1 Introduction

Slender structures are gaining more and more space nowadays. As well as the number of design and construction of large buildings and tall towers has been increasing every day. In the field of renewable energies, it can be seen a greater development of large wind turbines.

A worrying point about such structures, including wind turbines, is characterized by excessive vibrations that they may experience, whether due to more common dynamic loads such as wind and sea waves; or caused by various excitations such as engines, heavy traffic and even earthquakes [1].

Structural control is a solution that can be used to prevent excessive vibration levels in this type of structure. It can be classified as passive, active, hybrid and semi-active. This technology is based on the installation of external devices, as well as applying external forces, with the purpose of reducing high levels of structural vibrations, changing main structure stiffness and damping properties [2]. It is justified because the referred system, exposed to excessive vibrations, can suffer structural collapse and it is necessary, therefore, the use of techniques to keep the structure safe.

Hybrid control combines the properties of passive and active controls to complement and improve the performance of the passive control system and to decrease the energy requirement of the active control system, using actuators and energy sinks [3]. This controller requires much smaller actuator force magnitudes, compared to active control, which reduces cost, in addition to presenting better performance, when compared to the passive controller, expanding design frequency range [4, 5]. Occurring a power failure or failure of the active control component, the passive component of the hybrid control still offers some degree of protection [6]. The hybrid mass damper (HMD) is a combination of a tuned mass damper (TMD) with an active control actuator [7].

Saito, Shiba and Tamura [8] developed a hybrid damping system to reduce the dynamic response of two buildings with strong wind forces and medium-strength earthquakes in the city of Osaka in Japan. Two HMDs were installed on the upper floor of a 50-story structure building, 200-meter high steel structure to suppress translational and torsional vibrations. The other building had a 43-story triangular steel structure. From the earthquake observation data and the simulation results, the HMD system proved to be an excellent device for suppressing the last part of the vibration responses due to earthquakes.

Ahlawat and Ramaswamy [3] developed an optimal hybrid control system, driven by a diffuse logic controller (FLC). It has been demonstrated that the optimal values of the design parameters of the hybrid control system can be determined without specifying the modes to be controlled. The performance in terms of the structural response of the HMD, driven by FLC was considered better than that obtained using TMD or by an active mass damper (AMD) acting alone, and was considered very effective for the control of vibration in seismically excited buildings.

Avila and Gonçalves [9] proposed a parametric and detailed study to determine the weighting matrices using the instantaneous optimal control algorithm applied to an HMD to minimize the performance index previously established to ensure the system slender.

Collette and Chesné [10] proposed a hybrid mass damper to reduce the resonant vibration amplitude of a three degree of freedom structure, which could behave as an active mass damper to suppress vibrations induced by small earthquakes, and with a tuned mass damper to suppress vibrations in a targeted way, excited by a major earthquake.

According to the authors Yaqi Hu and Erming He [5], floating wind turbines are subjected to more severe structural loads than fixed-bottom wind turbines due to the additional degrees of freedom of their floating foundations. A vibration control strategy was developed for a floating wind turbine, installing an HMD in the turbine's nacelle to identify wind and wave disturbances. Then, a linear quadratic regulator controller (LQR) with state feedback was designed to reduce the vibrations and loads of the wind turbine. The results show that the control strategy of an HMD is effective and the designed controllers can further reduce the vibrations of the wind turbine under the restrictions of limiting stroke and power consumption.

In this work a numerical study of a hybrid mass damper control applied to a wind turbine subjected to wind and earthquake loads is performed. The performance of different control algorithms, such as: proportional integral derivative (PID), excellent classic (LQR) is compared. The results showed that the HMD was efficient in controlling the wind turbine dynamic response and it was also observed that the LQR controller showed a better performance than the PID controller.

2 Mathematical formulation

The structural system studied in this work is a tall, flexible and slender tower that supports at the top blades and nacelle of a large wind turbine. Although the real structure is a system with infinite degrees of freedom, it can be modeled as a discrete system with multiple degree of freedom (MDOF) [11]. This structure can be modeled as a system having N degrees of freedom with a TMD device installed on the top and subjected to external dynamic excitation. The effects of blade rotation and flapwise/edgewise blade vibration are not considered in this preliminary model. Figure 1 represents the schematic description of a tubular wind turbine structure in the form of a cantilever beam with a tip mass.

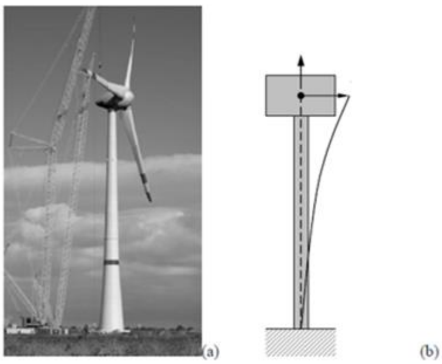

Figure 1. (a) Tubular structures of steel tower of wind turbines; (b) Schematic description of a cantilever beam with mass at the tip [1]

Considering systems of multiple degrees of freedom such as tall buildings and wind towers, the structural response can be obtained through a reduced model of a single degree of freedom, considering that type of structure vibrates predominantly in a single mode, usually the first [2, 3, 11].

In this study, the structural model of the wind turbine of multiple degrees of freedom is reduced to a single degree of freedom (SDOF) and a HMD, is connected to the main system with the aim to decrease the vibration amplitude of the main structure analyzed [1, 2].

Figure 2 shows the main structure reduced to a single degree of freedom, associated with the HMD composing the referred two degrees of freedom system, $\boldsymbol{M_1}$ is the mass of the main system, $\boldsymbol{K_1}$ is the stiffness of the main system, $\boldsymbol{C_1}$ is the damping of the main system, $\boldsymbol{M_2}$ is the HMD mass, $\boldsymbol{K_2}$ is the HMD stiffness, $\boldsymbol{C_2}$ is the HMD damping, $\boldsymbol{F}(t)$ is the dynamic load applied to the structure, $\boldsymbol{u}(t)$ is the control force, while $\boldsymbol{y}(t)$ and $\boldsymbol{z}(t)$ are the horizontal displacements of the main system and the HMD, respectively.

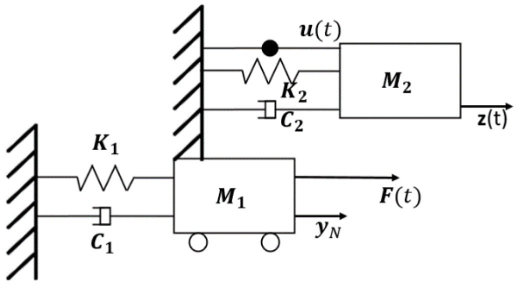

Figure 2. Two degrees of freedom model: main system + tuned mass damper with the $\boldsymbol{u}(t)$ actuator (HMD)

The equations of motion of the main system with a connected HMD, including the control force of $\boldsymbol{u}(t)$ are the following:

$$\boldsymbol{M_1}\ddot{\boldsymbol{y}}(t) + \boldsymbol{C_1}\dot{\boldsymbol{y}}(t) + \boldsymbol{K_1}\boldsymbol{y}(t) = \boldsymbol{F} \tag{1}$$

$$\boldsymbol{M_2}\ddot{\boldsymbol{z}}(t) + \boldsymbol{C_2}\dot{\boldsymbol{z}}(t) + \boldsymbol{K_2}\boldsymbol{z}(t) = -\boldsymbol{M_2}\ddot{\boldsymbol{y}}(t) + g(t) + \boldsymbol{u}(t) \tag{2}$$

3 Numerical Results

In this work, a study is carried out, applying structural control to a wind turbine, previously studied by Avila *et al.* [1], whose was reduced to a simplified model of a one degree of freedom subjected to a harmonic load $f(t) = 2500sin(\omega t)$ applied at the top of the tower and a seismic load corresponding to *El Centro* base acceleration [12]. The damping ratio, ζ, is assumed to be 2% of the critical value. The mass, damping and stiffness properties of the structure are, respectively, $\boldsymbol{M_1} = 34{,}899{,}00$ kg, $\boldsymbol{C_1} = 0{,}00$ Ns/m and $\boldsymbol{K_1} = 463{,}671{,}00$ N/m. The HMD properties were calculated using Den Hartog's equations [13]: $\boldsymbol{M_2} = 967{,}98$ kg, $\boldsymbol{C_2} = 427{,}6724$ Ns/m and $\boldsymbol{K_2} = 8{,}9096\text{x}10^3$ N/m.

Initially, the force on the HMD actuator was calculated using the LQR control algorithm. One of the factors that influences the achievement of good results through this algorithm is the choice of suitable weighting matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$. Equations (3) and (4) show the matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ adopted in this analysis, respectively, whose magnitudes are defined according to the relative importance given to state variables and control forces in the minimization process [9, 14].

$$\boldsymbol{Q} = \begin{bmatrix} 10^{10} & 0 & 0 & 0 \\ 0 & 10^2 & 0 & 0 \\ 0 & 0 & 10^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$\boldsymbol{R} = [1] \tag{4}$$

Figure 3 shows the block diagram of the LQR controller considering wind force excitation (represented by the sine excitation) and seismic excitation (represented by the *El Centro* earthquake), where **A** is the state matrix, **B** is the input matrix, **C** is the output matrix and ***G*** is the gain.

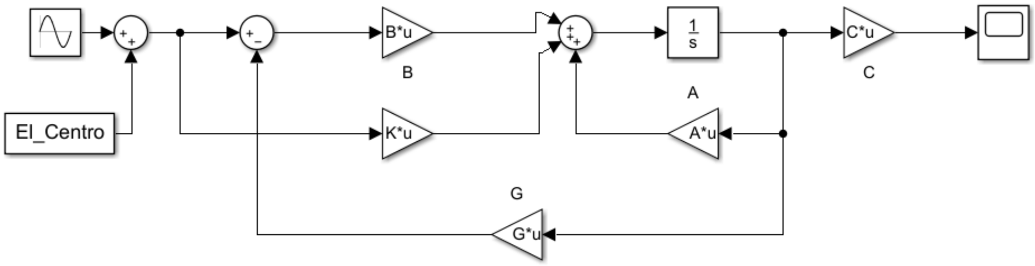

Figure 3. Block diagram of the LQR controller with HMD

Figure 4 shows the main structure displacement evolution comparing the use of a purely passive mass damper with the HMD use. It is considered seismic and wind excitations with LQR controller. It can be seen that the HMD demonstrated an excellent performance, reducing, approximately, up to 6 times the amplitude of vibration presented with the passive control.

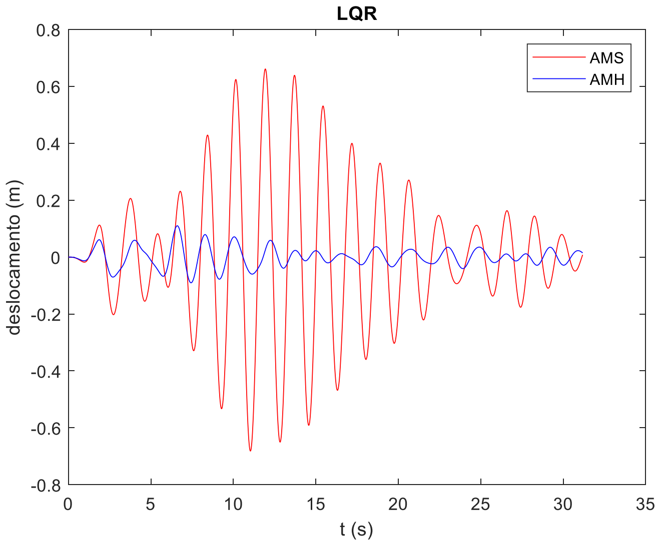

Figure 4. Time history of the displacement of the main system (TMD x HMD)

Then numerical simulations are performed using an HMD whose control force is obtained through the PID controller [15]. The gains of the PID controller were obtained through the Matlab computational package tuning tools. Figure 5 presents the block diagram of the PID controller for the hybrid mass damper, considering the same dynamic excitations of the last analysys.

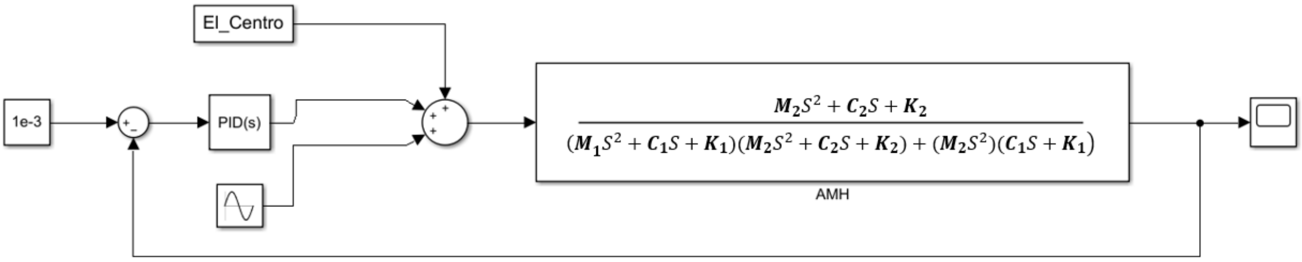

Figure 5. Block diagram of the PID controller with HMD

Figure 6 shows the comparison of the main system displacement time response, using the LQR and PID controllers. It can be verified that the LQR controller has a better performance than the PID controller, with a reduction, compared to the uncontrolled system response, of approximately 63% and 43%, respectively.

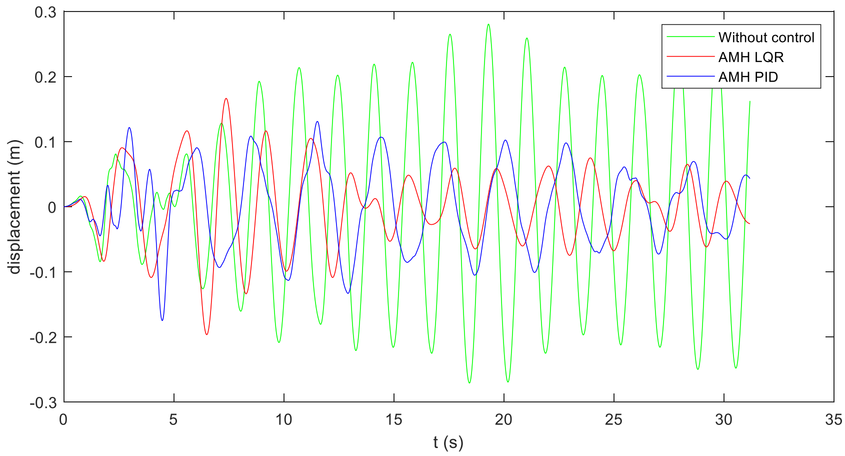

Figure 6. Displacement time history of HMD displacement using LQR and PID controllers

The value of the rms displacement obtained for the system without control was $0.2098\ m$, for the system with HMD LQR controller case it was $0.04506\ m$ and for the HMD PID controller case it was $0.09592\ m$. HMD with LQR and PID controllers, presented a response rms reduction of approximately, 78.5% and 54.3%, respectively.

Figure 7 shows the comparison of the time history control force required in the LQR and PID controller cases, where the maximum required force is$28030\ N$ and $2735\ N$, respectively. The required control force for the LQR case is approximately 10 times greater than the control force for the PID case. It is worth to mention that the LQR magnitude force is related to the weighting matrices considered

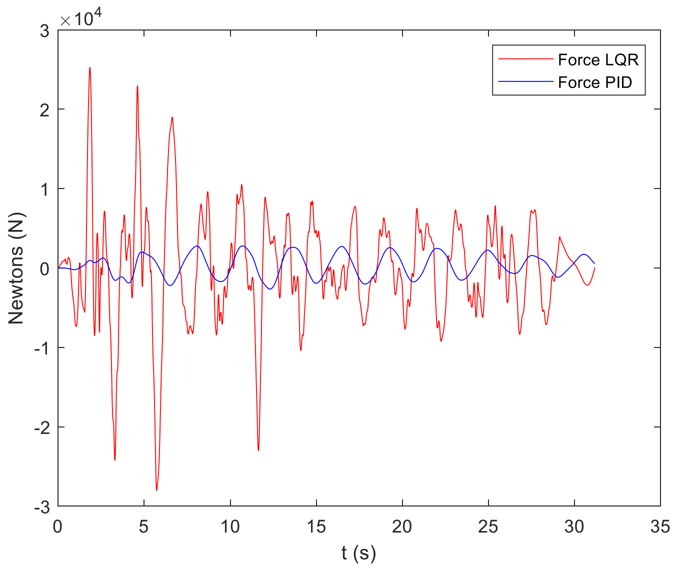

Figure 7. Time history of the control force magnitude required in LQR and PID

4 Conclusions

In this work, the use of an HMD is studied, in order to verify the potential of this device. The analysis were performed using the parameters of the wind turbine presented by Avila *et al.* [1]. The control forces are obtained through the two types of control algorithms, LQR and PID, which are analyzed numerically with external excitations of wind and earthquake.

Although the LQR controller has a better response and a lower rms value than the PID, the two controllers reduce the system to the same extent. The PID algorithm requires a control force magnitude ten times less than the LQR controller, which certainly impacts on the cost of the actuator.

For future work it is intended to implement this hybrid control in an experimental reduced model. It is also worth mentioning that this device shows potential, based on more in-depth future studies for use on a real scale.

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