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# STUDY OF A TRELLIS PYLON VIBRATIONS INDUCED BY WIND LOADS AND CONTROLLED TRHOUGH AN AMD

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**Abstract.** The rapid expansion of telecommunications infrastructure, driven by the deployment of the 5G network, necessitates innovative engineering solutions to ensure the reliability and stability of these critical structures. Steel trellis pylons, designed for hosting several telecommunication antennas, are particularly susceptible to wind-induced vibrations due to their slender profiles, high equivalent area exposed to wind loads and low structural damping. Such vibrations can lead to structural deterioration, signal disturbance, and, in severe cases, total structural failure. In this context, the need for effective vibration control measures is becoming more and more relevant. This paper underscores the complex challenge of wind-induced vibrations in telecommunications pylons and the promising potential of AMD systems as a mitigation strategy. This study aims at advancing the state of the art by integrating experimental wind load measurements, modal analysis, and the application of AMD technology to a 50-meter-high steel trellis pylon. Through comprehensive analysis and numerical simulation, the effectiveness of AMD systems in enhancing structural performance and resilience under wind loading conditions is validated.

## 1 INTRODUCTION

In recent years, especially because of the diffusion of the 5G internet network, it has become increasingly necessary to develop new solutions (such as trellis pylons) to install a growing number of antennas for the transmission of the electromagnetic signals, and to implement or improve the monitoring of existing infrastructure. Steel truss structures for telecommunications typically have very low damping values, even lower than 1%. Therefore, wind-structure interaction phenomena can generate significant oscillations, leading to structural deterioration, potential disturb of the network signal or, in the worst cases, the collapse of the system and a consequent total interruption of the service.

In this context, a detailed knowledge of the wind loads would allow to perform better structural analysis and estimate the beneficial effects of improvement interventions, such as the installation of a damping system or local structural reinforcements. Unfortunately, the modelling of wind actions induced on these structures is a complex and still open issue, and nowadays the national and international regulations introduce oversized safety factors in favour of safety. Regarding the possibility of adopting active strategies for controlling Wind Induced Vibrations (WIV), in recent years some solutions have been developed [1][2][3][4]. Rebecchi et al. [5][6] introduced the concept of using active control systems to mitigate seismic responses, a principle that can be extended to address WIV. Cii et al. [7] specifically addressed the application of Active Mass Dampers (AMDs) in controlling vibrations in slender steel structures, demonstrating their effectiveness in reducing oscillations due to wind loads. Furthermore, new solutions have been also presented to deal with systems nonlinearities [8][9].

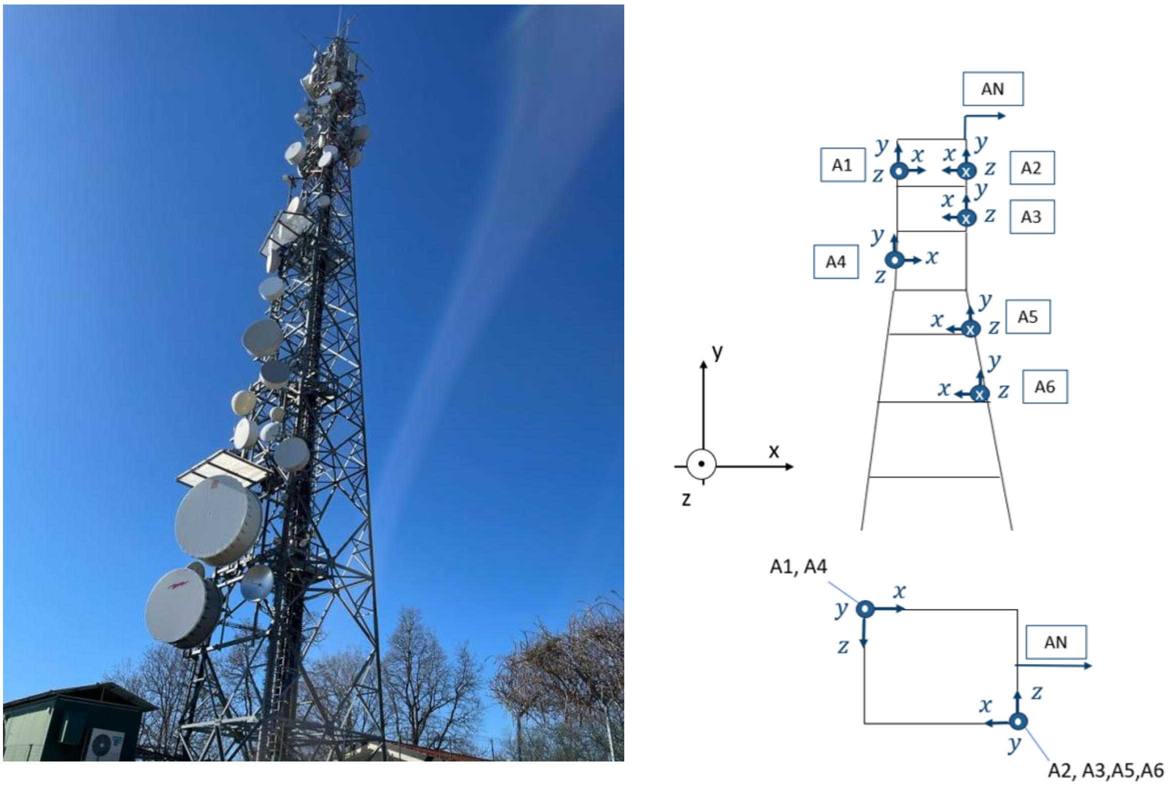
In this article we analyse a 50-meter-high steel trellis pylon located on the top of a mountain, at 1300 meters above sea level, in Liguria (Italy). Several accelerometers and one anemometer on the top were installed on the structure. The wind loads were estimated and a reduced modal model of the pylon, identified from the accelerometer measurements, was implemented in Matlab/Simulink considering only the most significant modes. Finally, an Active Mass Damper (AMD) was modelled, starting from the physical parameters of the motor and the control law, and added on the top node of the structure. From the numerical simulations it is possible to study the structure behaviour with and without the AMD system, comparing the indexes in terms of tip displacement, most stressed structural elements and acceleration at the antennas (or other critical equipment) installation points.

## 2. MATERIALS, MODELS, AND METHOD

This section outlines the methodology adopted for studying the WIV on the considered test case and the application of an Active Mass Damper (AMD) system to control these vibrations. The approach integrates experimental measurements, numerical modelling, and the design and implementation of an AMD system.

### 2.1 Test Case

The focus of this study is a 50 meters tall steel trellis pylon situated at the top a mountain in Liguria (Italy), at an elevation of 1300 meters above sea level. The structure, designed to host telecommunications antennas for the expanding 5G network, faces significant wind exposure due to its height and location (**Figure 1**a). To monitor the pylon's dynamic response to wind loads, several accelerometers (**Figure 1**b) were installed on the structure. Moreover, a directional anemometer was installed on the top of the tower. Two AMD units are designed to be mounted at the highest point of the pylon to study the effectiveness of vibration control.



(a) (b)

**Figure 1**: Picture of the steel truss tower (a) and Sensor scheme (b)

## 2.2 Wind Action

Wind load estimation is a research field deeply investigated over the last years [10] and it was a crucial aspect of this study. Wind speed and direction were continuously recorded by an anemometer located at the top of the pylon over four consecutive months from the end of June 2023 to the beginning of November 2023. These data, sampled at a frequency rate of 25 Hz in order to capture the structure's dynamic response to wind, allowed for a detailed analysis of the wind load distribution across the structure. The wind data was gathered in time histories of 10 minutes each. The synthetic max and rms values of each time history are shown in **Figure 2**. A maximum wind speed of 35.3 m/s was measured on Oct. 20th, 2023 at 08:35 am. This 10min time history was used in the following numerical simulations to study the dynamic response of the structure (**Figure 3**a). For each structural node, the force of the wind on the structure is a function of:

- wind speed (sampled at height equal to 50 meters);
- height from the ground in accordance with the logarithmic wind profile, considering the reference wind speed measured by the anemometer installed at h=50 m (**Figure 3**b);
- reference area for each node, determined by the geometry of the structure (considering also the area of antennas, satellite dishes or other devices installed on the structure).

As a first approximation, in this paper the force exerted on the generic node $n$ is thus computed accordingly to the following formulation:

$$F_n(t) = \frac{1}{2}\rho A_n C_{d,n} W_n^2(t) \tag{1}$$

where $\rho$ is the air density, $A_n$ is the reference area of node $n$, $C_{d,n}$ is the drag coefficient associated to the node $n$, $W_n(t)$ is the wind speed at each node. The latter is obtained by the following computation:

$$W_n(t) = LWP(h_n) * W(t) \tag{2}$$

where $h_n$ is the height of node n, $LWP$ is the normalized Logarithmic Wind Profile (**Figure 3**b) and $W(t)$ is the wind speed experimentally measured by the anemometer (**Figure 3**a). So, calculating the force acting on each node is now possible to define a nx1 vector of physical forces:

$$\bar{F} = \begin{bmatrix} F_1 \\ \dots \\ F_n \end{bmatrix} \tag{3}$$

Finally, it is possible to calculate the modal components of the external forces as:

$$\bar{F_q} = \Phi^T * \bar{F} \tag{4}$$

where Φ is the mode shapes matrix, with dimensions $nxm$, obtained from a FEM model of the pylon, and $m$ is the order of the reduced modal model.

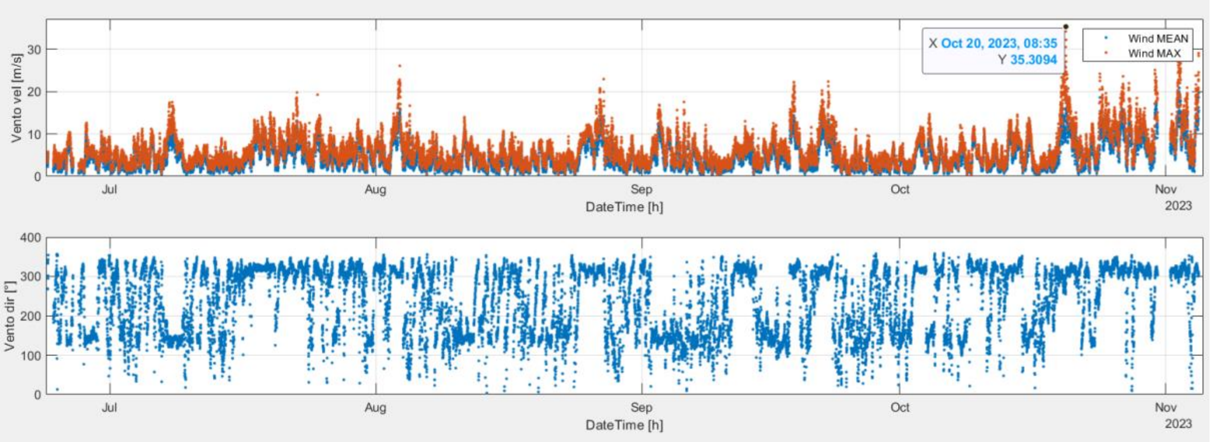
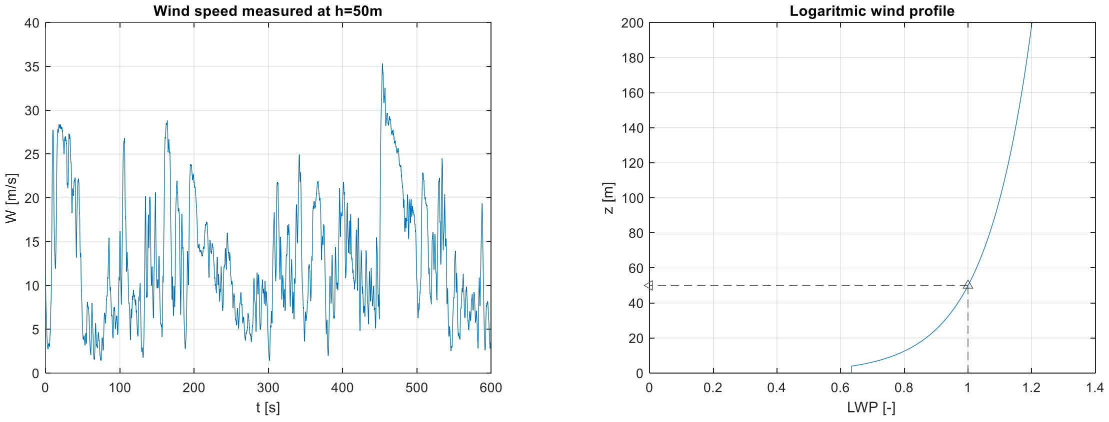


**Figure 2**: Sampled wind speed and direction

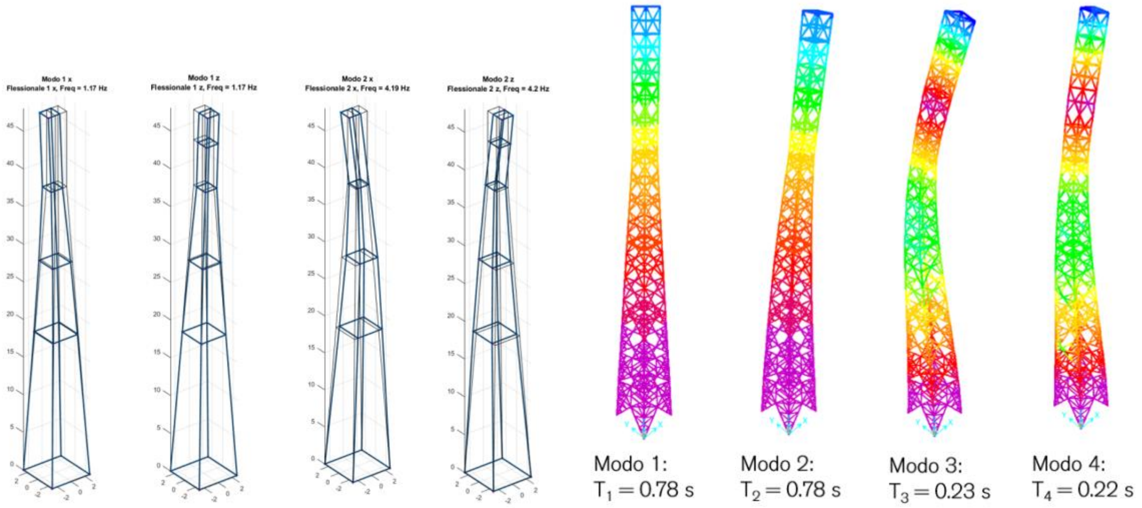


(a) (b)

**Figure 3**: Wind speed experimentally measured at height equal to 50 meters (a) and Logarithmic wind speed profile, normalized to 1 at height 50 meters (b)

## 2.3 State-Space Modal Model

Using the accelerometers data an Operational Modal Analysis (OMA) is performed. OMA allows to experimentally determine the structural natural frequencies and damping ratios. Also, the mode shapes of the structure are obtained thanks to accelerometers distributed in different locations of the structure (**Figure 4**a).



(a) (b)

**Figure 4**: First 2 bending mode shapes, in x and z direction, identified by the OMA (a) and first 4 mode shapes extracted from FEM model in SAP2000 (b)

On the other hand, a complete modal model of the trellis pylon was developed using the SAP2000 structural analysis software (**Figure** 4b). The model incorporated each structural component, including antennas, modelled as concentrated masses at their respective installation nodes. This approach allowed for a close correlation between the computed natural frequencies and the experimental frequencies measured on-site. The matrices modal mass $[M_r]$ and stiffness $[K_r]$ matrices are extracted from the FEM model and used to implement a State-Space model in Simulink:

$$A = \begin{bmatrix} [M_r] & [0] \\ [0] & [I] \end{bmatrix}_{2mx2m}$$

$$B = \begin{bmatrix} [C_r] & [K_r] \\ -[I] & 0 \end{bmatrix}_{2mx2m} \tag{5}$$

The damping matrix $[C_r]$ is obtained by means of the proportional method ($[C_r] = \alpha[K_r] + \beta[M_r]$), where the $\alpha$ and $\beta$ coefficients are calculated from the experimental damping ratios obtained from the OMA. The Simulink model (**Figure 5**) is then adopted to simulate the system dynamic with and without the Active Vibration Control (AVC).

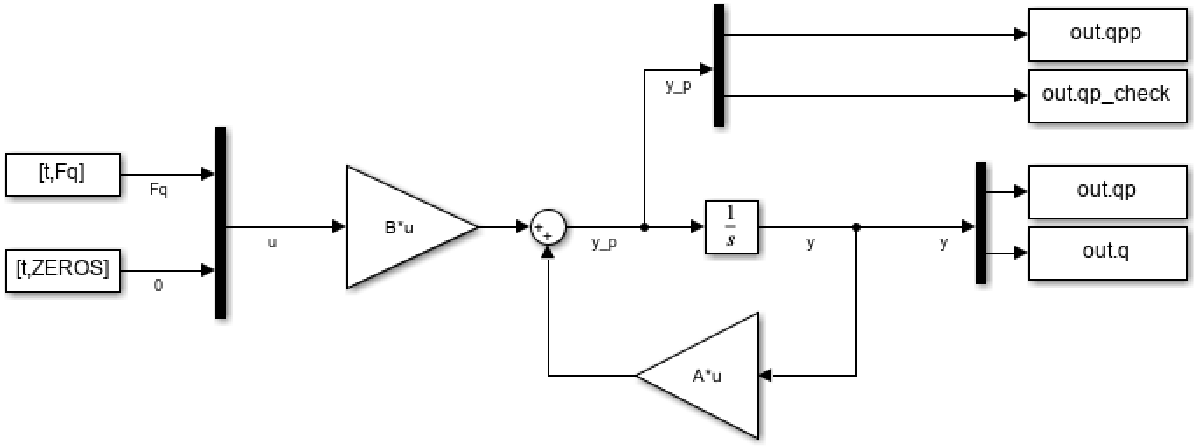


**Figure 5**: State Space model of the uncontrolled structure implemented on Simulink

## 3. CONTROL LOGIC

This section details the control logic, focusing in particular on the implementation of an Active Mass Damper (AMD) system. Given the structure's susceptibility to wind excitations and its low self-damping, an AMD system offers a dynamic solution to enhance the pylon's damping characteristics, thereby improving structural resilience and reducing oscillation amplitudes.

### 3.1 Active Mass Damper (AMD) System Overview

The AMD system is composed of a pair of linear motors, each driving a mass along a track, and a control unit that generates the motion of these masses based on real-time structural response data. These components are installed at the pylon's highest accessible point, where their effectiveness in modifying the structure's dynamic response is maximized. The AMD main components are:

- Linear Motors: Capable of generating a maximum force of 1 kN, these motors move the masses in directions orthogonal to each other, allowing independent control over different oscillation components of the structure.
- Masses: Each mass, driven by its respective linear motor, is selected based on the structural modal properties and the desired damping effect. The inertial forces associated to the masses counteracts the wind-induced motions.
- Control Unit: This unit processes signals from accelerometers located on the pylon and, using a predefined control logic, determines the reference motion for the masses to effectively dampen structural vibrations.

**Figure 6**: Picture of the 2 AMDs installed on a trellis mock-up realized in the ISAAC laboratories

### 3.2 Sky-Hook Control Logic

The control strategy employed is the well-known Sky-Hook [11][12][13]. The control law is:

$$F_c = -G * v_{roof} \tag{6}$$

with the control force proportional to the structure rooftop speed by means of a adjustable constant (*G*) and the minus sign in order to have a dissipating effect on the structure. The proportional gain is a critical parameter in the Sky-Hook control logic. It determines the magnitude of the force exerted by the AMD in response to structural motion, directly influencing the system effectiveness in increasing structural damping. The correct value of *G* is chosen in two steps:

- Initial Estimation: Based on the structural properties and AMD specifications, an initial value for *G* is estimated so to increase the overall structural damping of the first mode of the structure by a desired value (5%, considering that the uncontrolled structure has a very low damping of 0.4 %).

Assuming that the motion of the structure is dominated by the first mode only, both in x and in z direction, the initial guess for the gains is set as:

$$
\begin{aligned}
G_x &= \frac{2m_1 w_{0,1} * \xi_{agg,1}}{\Phi_{n,1}} = 148.7\frac{kNs}{m} \\
G_z &= \frac{2m_2 w_{0,2} * \xi_{agg,2}}{\Phi_{n,2}} = 148.6\frac{kNs}{m}
\end{aligned}
\tag{7}
$$

- Numerical Simulation: Simulations in MATLAB/Simulink, including the wind load model and the structural modal model, are used to refine *G*. The objective of time history simulation is to verify which is the actual force generated by the AMD in a real-case scenario. The force needs to be within the characteristic curve of the motor and the stroke requires to respect the linear actuator limits.

To simulate the AMD behaviour under the described conditions, the state space model of the structure is enriched adding the feedback action of the control force generated by the AMD, as shown in **Figure 7**.

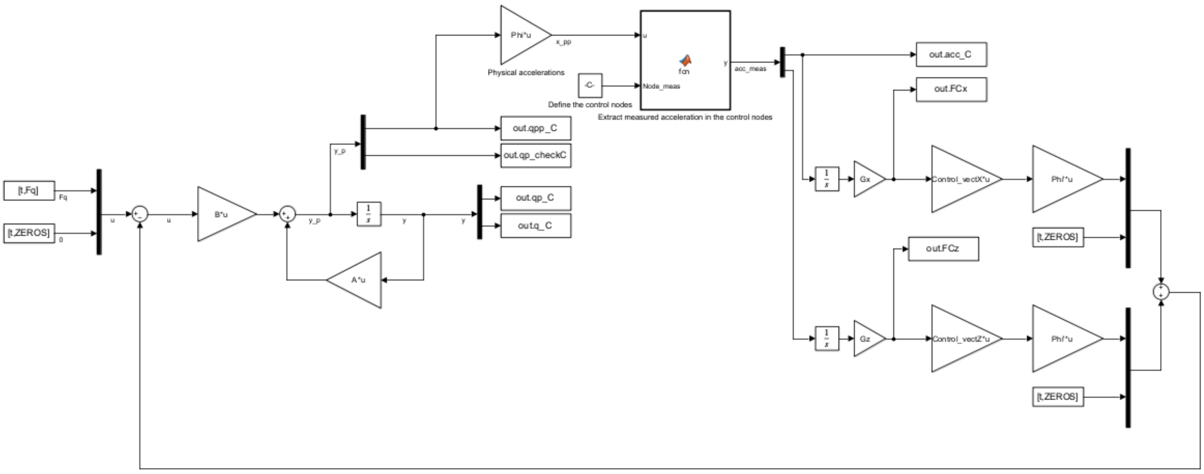
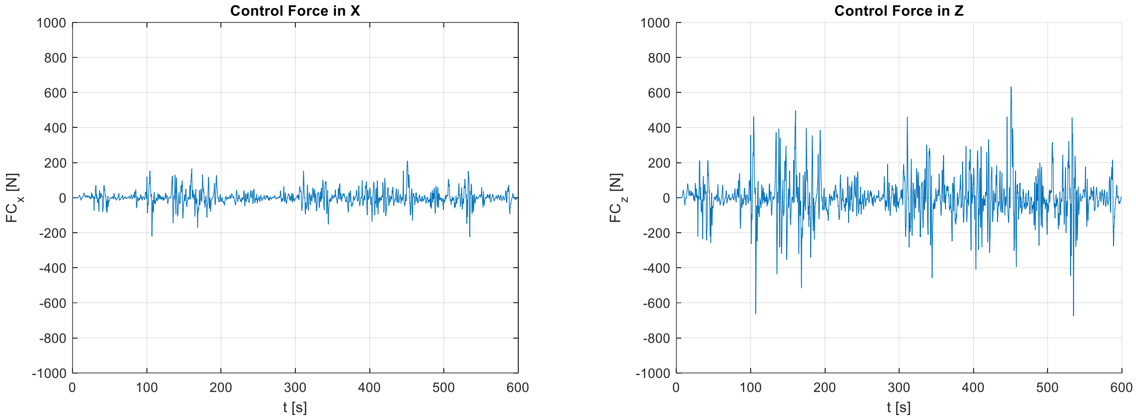


**Figure 7**: State Space model of the controlled structure implemented on Simulink

Basically, from the state space modal model the physical accelerations of all the system nodes are obtained and the time history of control node is extracted (both in x and z directions). Accelerations are then integrated to obtained vibration velocities and multiplied by the gains ($G_x$ and $G_z$) to compute physical forces. The physical forces are converted in modal components and given as negative feedback to the state-space modal model.

The forces exerted by the AMD in x and in z directions are shown in **Figure 8**. The maximum force required to the AMD is 224 N in the x direction and 674 N in the z direction (most influenced direction by the wind time history considered). It can be observed that even in the most loaded direction the peak is well below the limit of the AMD (1 kN). In order to correctly design the moving mass, the limit stroke of 0.5 m is considered and, imposing the minimum value that satisfy the requirements, the mass is set equal to 50 kg.

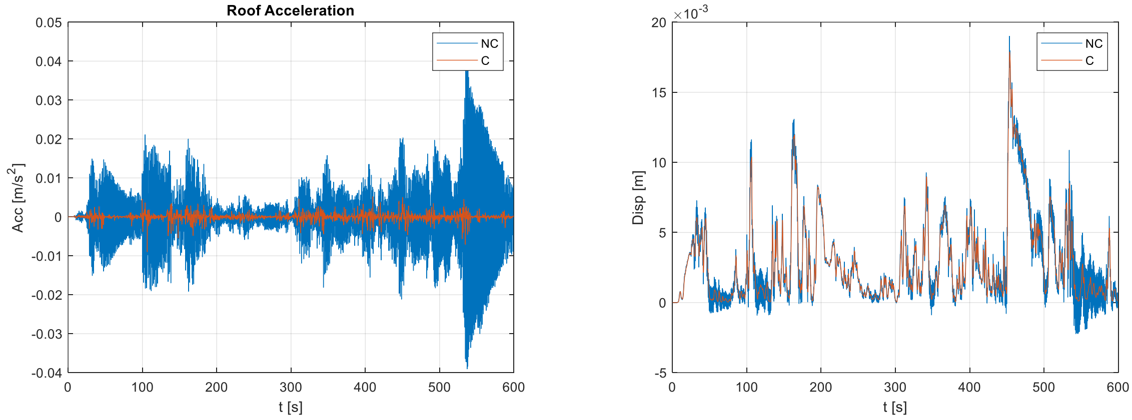


(a) (b)

**Figure 8**: Control force exerted by the AMD in x (a) and z (b) direction

# 4. RESULTS AND DISCUSSION

In this section the outcomes derived from both experimental measurements and numerical simulations, focusing on the effectiveness of the AMD system in mitigating WIV, are presented. The analysis compares the structural responses with and without the AMD system under the same wind conditions.



(a) (b)

**Figure 9**: Rooftop acceleration (a) and displacement (b) without control and with active AMD system

The simulations study 2 different critical aspects of the structure subjected to wind loads. Firstly, the acceleration at Critical Points is analysed. Acceleration at the rooftop, where the antennas and other critical equipment are installed, shows a very significant decrease (-78%), passing from 4.1 cm/s^2 for the uncontrolled system to 0.9 cm/s^2 for the controlled structure (Figure 9a). This implies an improved operational stability and reduced risk of equipment damage. Secondly, the tip displacement is verified. The AMD ensures a slight decrease (-6%) on the overall tip displacement passing from 19.0 mm to 17.9 mm (Figure 9b). This is because the tip displacement is almost completely generated by the static component of the wind, that cannot be controlled by the AMD.

## 5. CONCLUSION

This study presented the effectiveness of an Active Mass Damper (AMD) system in mitigating wind-induced vibrations in a 50-meter-high steel trellis pylon. Through a combination of experimental measurements and numerical simulations, the dynamic behaviour of the structure under wind loads was assessed and the impact of the AMD system was verified. By reducing the amplitude of oscillations and stress levels, the AMD system contributes to the operational stability of telecommunications equipment and extends the structural service life, thereby enhancing overall safety.

The implementation of a Sky-Hook control logic proved to be highly efficient. The proportional gain tuning was optimized, ensuring significant damping enhancement and minimal energy consumption. The maximum force required to the AMD is 1 kN, with a linear mass of only 50 kg. The reduction effect on the tower vibrations is almost 80%.

As a next step of this research, a better model of wind actions can be developed, integrating the effects of wind-structure interaction in the control logic. This will further improve the performances and optimize the control effort for different wind scenarios.

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