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Wind induced vibrations of a high tapered obelisk: wind tunnel tests, numerical analysis and design of countermeasures

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Abstract

The structure studied in this paper is a 85 meters high tapered obelisk, made of reinforced concrete for the first 9 meters and of steel welded plates for the upper 76 meters. Its bluff cross section consists of two closely spaced triangular sections that are scaled linearly with the height from ground. Having a complex bluff section and being a light structure, aerodynamic instabilities and vortex induced vibrations were investigated using a mixed experimental-numerical approach, in order to define wind loads for the structural design, and possible interventions aimed at mitigating the dynamic effects due to wind action. Exploiting the regular tapering of the obelisk section, a rigid sectional model with constant section was initially tested in wind tunnel: static aerodynamic coefficients and vortex-induced response as a function of the Scruton number were measured for several angles of attack. The experimental sectional results were successively used to assess numerically the response of the structure considering tapering, the gradient of wind speed, the modal shapes, and the correlation of wind actions. Even though the numerical analysis showed that the tapering drastically reduces aerodynamic issues, the achieved results underlined the pressing need to increase the damping of the structure in order to avoid galloping and vortex induced vibrations for wind speeds within the design range; to this aim tuned mass dampers were designed.

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Keywords: vortex induced vibrations; galloping; wind tunnel; slender structure; tapered structure; tuned mass damper

1. Introduction

High-rise slender structures with bluff cross-sections are likely to be prone to vortex-induced vibrations and aerodynamic instabilities, such as galloping, that can jeopardize their structural integrity. Therefore, at the design stage, thorough analyses must be performed to assess possible wind-structure interaction related problems. For unconventional cross-sections, wind tunnel studies on scaled models are required to determine the steady and unsteady aerodynamic coefficients and to assess the damping which is necessary to suppress vortex-induced vibrations (VIV), if necessary [1,2,3,4].

Usually, for structures with constant cross-sections, wind tunnel tests may be limited to sectional models: tridimensional features such as correlation length of aerodynamic forces, effect of model shapes, and effect of wind speed profile can be assessed numerically. On the contrary, full aeroelastic models are required if the structure has a variable cross-section or a complex tridimensional shape. A particular situation occurs when a slender structure with a regular taper is considered, since cross-sections maintain the same geometry and they are scaled linearly with height. In this case, even if the cross section is complex (either

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geometrically or aerodynamically) a hybrid approach is possible: the cross-section is first studied experimentally in wind tunnel using a sectional model. In such tests, both the possibility of using a larger length scale (e.g. in the order of 1:10 versus 1:200 typically) and the easiness of investigating the dependence of VIV upon the Scruton number (i.e. upon the structural damping value of the full-scale structure) can be easily exploited. The effects of the tapering are subsequently assessed by means of the numerical approach that is discussed in the following sections. In general, tapering mitigates the vortex induced vibration amplitude and widens the range of critical wind speeds, as it has been already reported by other researchers that studied full aeroelastic towers with simple sections [5,6].

The tapered structure that is studied in this paper is shown in Fig.1. The structure is an 85 meters high tapered obelisk, in which a reinforced concrete structure is present for the first 9 m, while the upper 76 meters are made of welded steel plates. Its bluff cross-section consists of two closely spaced triangular sections that are scaled linearly with the height from ground (see Fig. 2). The two sections are connected at the top of the obelisk. The first two bending modes of the obelisk have natural frequencies equal to 1.14 Hz and 1.62 Hz, with an equivalent modal mass per unit length of 730 and 1572 kg/m, respectively. Their modal shapes, in which the two sections move as if they were a rigid shape, are shown in Fig. 3.

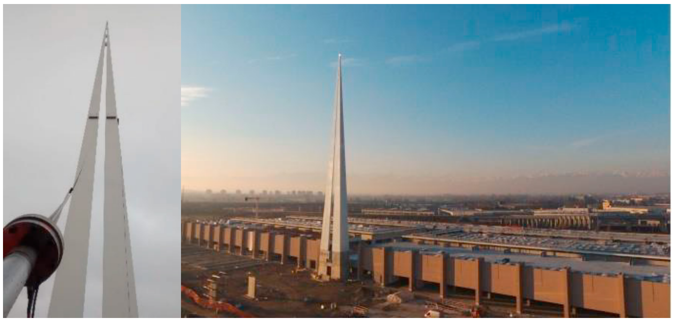

Fig. 1. (a) Tapering of the obelisk (b) overview of the obelisk.

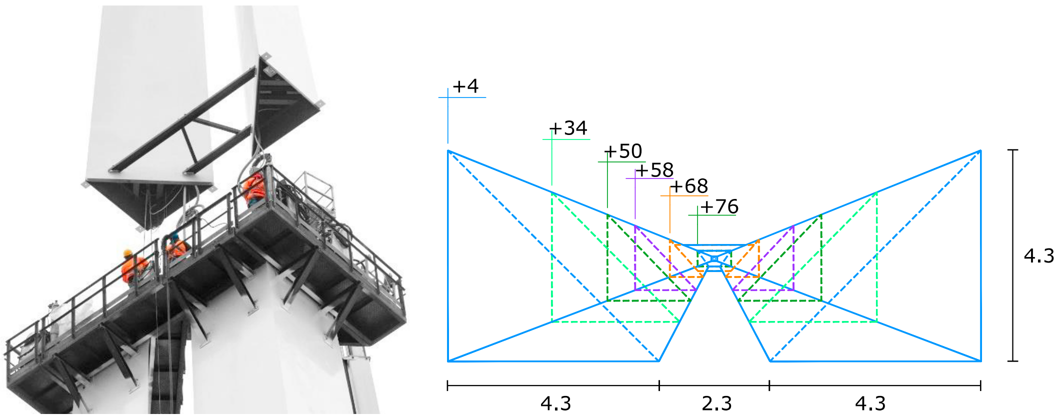

Fig. 2. (a) Picture of the construction stage where it is possible to see the cross-section; (b) Cross sections at different heights (in m)

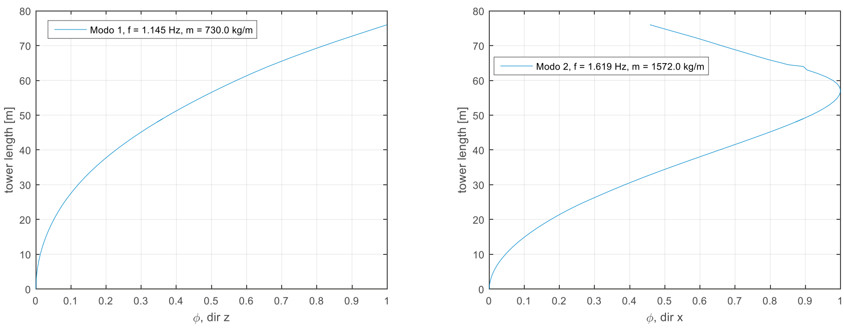

Fig. 3. (a) Mode 1: first bending mode along z direction (see Fig. 4 for conventions); (b) Mode 2: first bending mode along x direction

2. Wind Tunnel Tests

2.1. Sectional tests

Wind tunnel tests were carried out using a sectional model with constant section, having a depth dimension D = 0.254 m (considering a full-scale section at height 55m, D = 1.43 m; therefore, a length scale $\lambda_L \approx 1:6$ can be assumed). Static aerodynamic coefficients where measured both by means of external multi-axis balances and by integrating pressure distributions measured with a dense ring of pressure taps. Vortex-induced vibrations where measured for a limited set of wind angles of attack (-4 and -35 deg), that where selected analyzing the magnitude of unsteady forces during static tests. For VIV tests the model was elastically suspended on springs, and VIV were measured investigating a wide range of wind speeds and several structural damping values.

2.2. Experimental Results

Fig. 5a shows the measured static aerodynamic coefficients as a function of the angle of attack α , while Fig. 5b shows the quasi-steady aeroelastic coefficients, computed from the static ones, that can be used to assess the aerodynamic stability of the first vibration modes (e.g. galloping). A critical angle is at $\alpha = 70$ deg, where the direct aerodynamic damping term K_L+C_D is negative, being C_L and C_D the lift and drag coefficients, and K_L the slope of C_L.

As an example of VIVs results, Fig. 6a shows the VIV in z direction as a function of the reduced wind speed, for different damping values of the model (denoted as ζ_M in the figure), at the angle of attack $\alpha = -4$ deg. In this case, it is possible to notice two different lock-in ranges, due to the complex shape of the cross-section. Fig. 6b reports the maximum vibration amplitude in z-direction for each lock-in region as a function of the Scruton number. In addition, also the results for -35 deg angle of attack are reported. This information (y/d as a function of Scruton number) is used in the numerical approach, as detailed in Section 3.

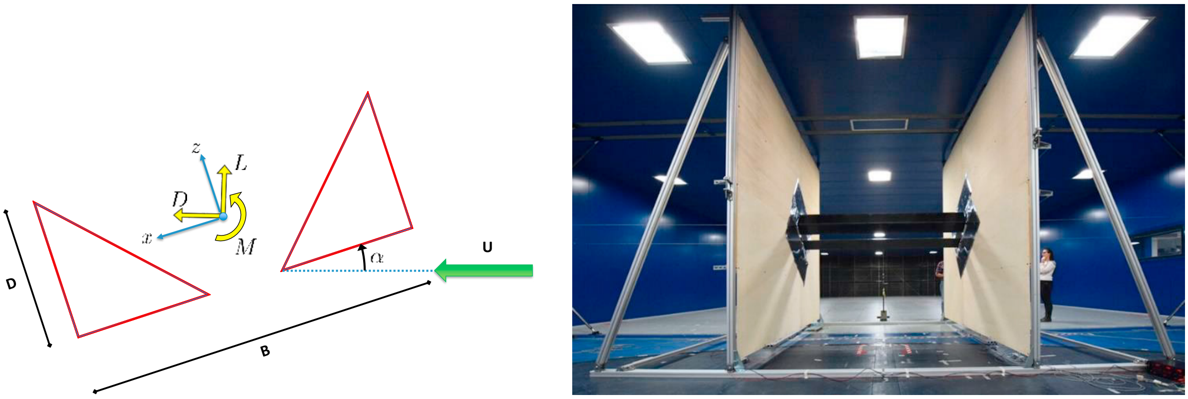

Fig. 4. (a) Nomenclature and sign conventions; (b) Sectional model in the wind tunnel of Politecnico di Milano: VIV tests at $\alpha = -35$ deg.

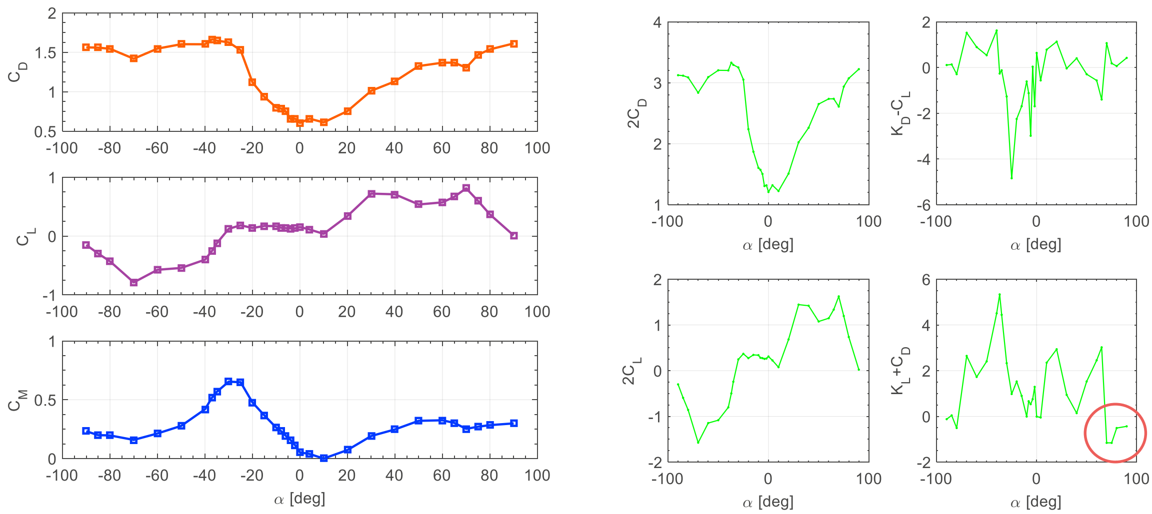

Fig. 5. (a) Steady aerodynamic coefficient; (b).Quasi- Steady aeroelastic coefficients

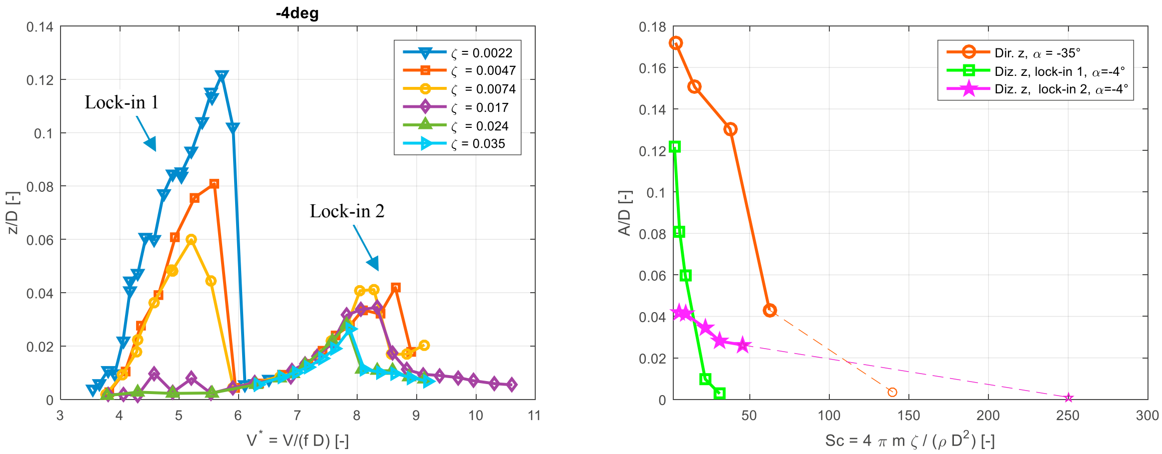

Fig. 6. (a) VIV in z direction as a function of the reduced wind speed, for different damping values of the suspended model, at the angle of attack -4 deg; (b) VIV amplitude in z-direction as a function of Scruton number, at the angle of attack -4 and -35 deg.

3. Numerical assessment of full-scale VIV on the tapered obelisk

The calculation of the crosswind amplitude is performed using the energy balance principle (EBP), considering the resonant response of the structure subjected to harmonic vortex-shedding in lock-in conditions. The EBP states that, during steady-state vortex-induced vibrations, the energy introduced into the system by the vortex shedding mechanism (E_w) equals the energy dissipated by the structural damping (E_d). Therefore, the equilibrium condition is:

$$E_w = E_d \tag{1}$$

3.1. Sectional Model

Considering the sectional model of length L, with cross-section of depth D, with a resonant harmonic displacement y, the energy introduced by the wind action in one oscillation cycle is

$$E_w = \int_0^L e_w ds = (\rho f^2 D^4 \,\mathrm{L}) \frac{\pi}{2} \frac{1}{\mathrm{St}^2} \frac{y}{D} (C_L \text{'} \sin\varphi) \tag{2}$$

where e_w is the energy introduced per unit length; ρ is the air density; f the vibration frequency; U is the wind speed; $St = fD/U$ is the Strouhal number; C_L' is the aerodynamic crosswind force coefficient of vortex shedding; and φ is the phase lag between aerodynamic force and displacement.

The energy dissipated by the structure is:

$$E_d = (\rho f^2 D^4 L)\mathrm{Sc}\, 2\pi^2 \left(\frac{y}{D}\right)^2 \tag{3}$$

where we have introduced the Scruton number $Sc = 4\pi m\zeta / (\rho D^2)$, being ζ is the structural damping coefficient and m the linear mass. At steady state VIV, the energy balance eq. (1) holds, therefore the combination of eq. (2) and eq. (3) leads to:

$$\frac{y}{D} = \frac{1}{\mathrm{St}^2} \frac{1}{\mathrm{Sc}} \frac{(C_L \text{'} \sin\varphi)}{4\pi} \tag{4}$$

This equation is in general nonlinear in *y/D*, because $(C_L \text{'}\sin\varphi)$ is a function of *y/D*. Having measured the steady VIV as a function of Sc (see Fig. 6b) it is possible to estimate $(C_L \text{'}\sin\varphi)$ as a function of *y/D* from eq. (4), as reported in Fig. 7a. The non-linear dependence of $(C_L \text{'}\sin\varphi)$ upon *y/D* is more than evident.

3.2. Deformable tapered obelisk

Considering the tapered obelisk, for each cross-section at a given height s, the energy per unit length introduced by the wind action is (using $C^* = C_L{}'\sin\varphi$)

$$e_w(s) = \pi \frac{1}{2} \rho U(s)^2 D(s) \mathrm{C}^*(s) y(s) \tag{5}$$

Denoting q as the steady state non-dimensional amplitude of the modal coordinate, the displacement y can be expressed as:

$$y(s) = \bar{D}\phi(s) q \tag{6}$$

where $\bar{D} = D(\bar{s})$ is a reference length at a given reference height $\bar{s}$, and ϕ is the modal shape. Introducing the Strouhal number, using $\bar{U} = U(\bar{s})$ as a reference speed and $\bar{D}$, $St = f\bar{D}/\bar{U}$, the energy per unit length is written as

$$e_w = (\rho f^2 \bar{D}^4) \frac{\pi}{2} \frac{1}{\mathrm{St}^2} \left[\left(\frac{U}{\bar{U}}\right)^2 \left(\frac{D}{\bar{D}}\right) C^* |\phi| \right] q \tag{7}$$

where the terms in the square brackets are a function of s. Integrating over the length of the correlation length $L_c = B - A$, between $s = A$ and $s = B$, the energy introduced into the system by the vortex shedding mechanism is

$$E_w = \int_A^B e_w ds = L \int_{A/L}^{B/L} e_w d\tilde{s} = (\rho f^2 \bar{D}^4 L) \frac{\pi}{2} \frac{1}{St^2} \int_{A/L}^{B/L} \left[\left(\frac{U}{\bar{U}}\right)^2 \left(\frac{D}{\bar{D}}\right) C^* |\phi| \right] d\tilde{s}\, q \tag{8}$$

If we introduce the Scruton number $Sc = (4\pi\tilde{m}\zeta)/(\rho\bar{D}^2)$ where $\tilde{m}$ is the equivalent modal mass per unit length $\tilde{m} = L\int_0 m\phi^2 d\tilde{s} / L\int_0 \phi^2 d\tilde{s}$, the energy dissipated by the structure can be written as

$$E_d = \left(\rho f^2 \bar{D}^4 L \int_0^1 \phi^2 d\tilde{s} \right) Sc 2\pi^2 q^2 \tag{9}$$

At steady state VIV, the energy balance leads to:

$$q = \frac{1}{\mathrm{St}^2} \frac{1}{\mathrm{Sc}} \left(\int_{A/L}^{B/L} \left(\frac{U}{\bar{U}}\right)^2 \left(\frac{D}{\bar{D}}\right) C^* |\phi| d\tilde{s} \Bigg/ \left(4\pi \int_0^1 \phi^2 d\tilde{s} \right) \right) \tag{10}$$

which corresponds to equation (E.7) of EN 1991-1-4:2005 for deformable structures. The term in the brackets corresponds to the norm coefficient $KK_w c_{LAT}$ [7].

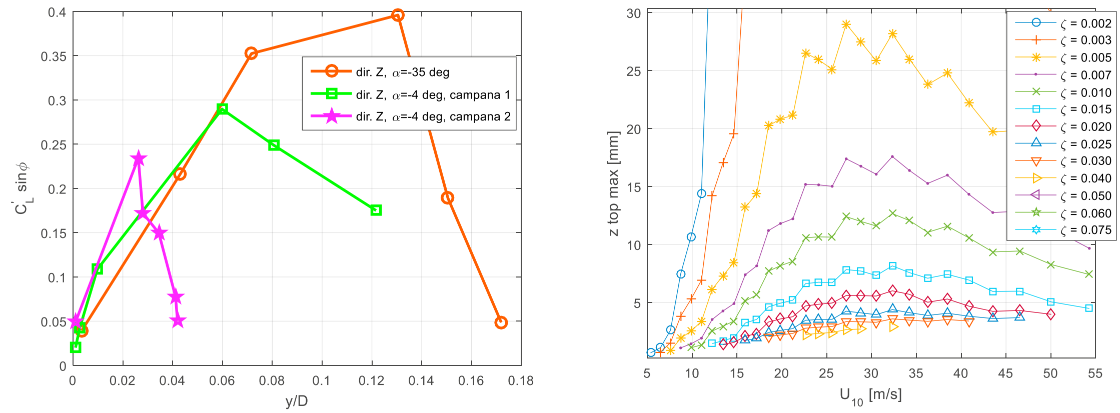

Fig. 7. (a) $(C_L{}'\sin\varphi)$ as a function of y/D; (b) top tower displacement in z-direction (1st mode) as a function of wind speed and damping.

Combining the information about modal shape, $(C_L{}'\sin\varphi)$, wind speed profile $U(s)$, cross-section dimension $D(s)$, selecting a correlation length, and considering several reference heights $\bar{s}$, it is possible to apply eq.(10) and to assess the VIV level for each mode. The correlation length is selected coherent with the measured lock-in ranges in terms of reduced velocity, and considering the variation with height of D and U. As an example of computed response, Fig.7b shows the VIV of the 1st mode a tower top as a function of the incoming wind speed, for several damping values ζ. Due to the taper vibration levels are reduced (w.r.t. constant section), but a very large lock-in range of wind speed is present: ζ less than 0.007 can lead to vibration levels that give fatigue problems.

4. Numerical assessment of aeroelastic stability

Adopting a quasi-steady approach, the aeroelastic damping forces per unit length can be written as

$$\begin{bmatrix} F_X \\ F_Z \end{bmatrix} = -0.5\rho UB \begin{bmatrix} 2C_D & K_D - C_L \\ 2C_L & K_L + C_D \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{Z} \end{bmatrix} \tag{11}$$

according to the sign conventions reported in Fig.8a; the values of the coefficients are reported in Fig 5b. Considering both modes and integrating over the total length of the obelisk, considering all the variations with height, it is possible to assess the aerodynamic damping ζ_{aero} for both modes as a function of the incoming wind speed at 10 m height, U_{10}. Fig.8b shows the ζ_{aero} for the 2nd mode at $\alpha = 70$ deg, which is the most critical situation. At the design wind speed for stability ($U_{10} = 30$ m/s) the mode has a negative aerodynamic damping equal to -0.005, that is comparable to the expected structural damping of the structure (i.e. it is expected that the total damping will be negative for wind speeds larger than 30 m/s).

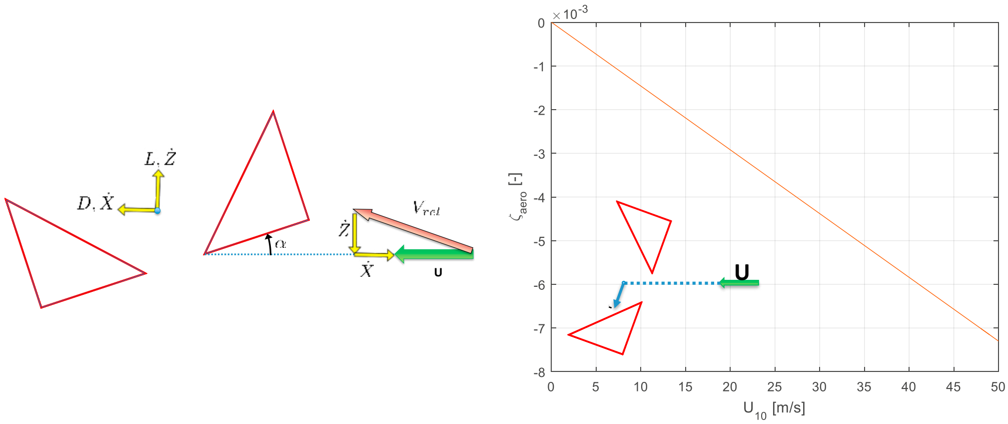

Fig. 8. (a) aeroelastic force conventions; (b) ζ_{aero} for the 2nd mode at $\alpha = 70$ deg.

5. Conclusions

A mixed experimental-numerical approach was used to assess the aeroelastic performances of a tapered obelisk. Both VIV and stability were investigated. Even if the tapering of the obelisk strongly reduces aerodynamic issues, the expected structural damping itself cannot guarantee an adequate safety level, therefore an additional damping system (TMD) should be installed on the structure.

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