THE TELECOMMUNICATION TUBULAR TOWERS WITH HELICOID STRAPS: DESIGN CONSIDERATIONS VS CFD MODELING

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ABSTRACT

Some regulations and fundamental aspects for the design of helicoid straps for telecommunications towers are presented and minimally summarized, as referred in integral form in the integrated master of science thesis of the first co-author. The software Ansys Fluent was used to analyze the influence of a methodology of applying helix straps to a tubular telecommunications tower, for suppression of the harmful effect of the structural vibrations due to vortex shedding.

Keywords: Telecommunication towers, cylindrical masts, helicoid straps, CFD.

INTRODUCTION

In recent years, a number of accidents occurred associated with wind induced vortex shedding vibrations of slender tower. Vibrations induced by the wind, when operating in significant specific periods, can trigger a tower dynamic response creating cumulative fatigue damage and that ultimately can lead to fatigue failure.

The disastrous effects of critical vibrations aggravated by vortex shedding phenomenon, can lead to large displacements of masts, towers, and/or their constitutive members, causing fatigue damage, buckling effects, and a succession of secondary order effects. When the structure require special control of this potential occurrence, damping devices can be used from simple resonators to the insertion of aerodynamic devices such as bands and helical straps (Freitas 2015, Freitas et al. 2015(a).

In the first part of this article, the vortex shedding vibrations are complemented with reference to: boundary layer and the separation phenomenology, lock-in, ovalization of tubes, and a final mention about general aerodynamic damping devices for vortex shedding minimization. Reference is made to the Eurocode design (EN 1993-3-2 and EN 1991-1-4) of helix strakes by two methodologies.

In the second part of this article, the software Ansys Fluent was used to analyze the influence of a methodology of applying helix straps to a tubular telecommunications tower, for suppression of the harmful effect of the structural vibrations due to vortex shedding (Freitas et al., 2015-b). For that objective, two types of towers were studied: simple and with helix strakes. As a standard case, the considered tower has a diameter D=1.2 m, wall thickness 6 mm and height 22 m. The design conditions used were identical in both tower types, as well as the CFD boundary conditions; but the roughness effects were not taken into consideration.
VORTEX SHEDDING VIBRATIONS

Vortex-shedding occurs when vortices are shed alternately from opposite sides of the structure. This gives rise to a fluctuating load perpendicular to the wind direction. Quite detrimental resonant structural vibrations may occur if the frequency of vortex shedding is the same as a natural frequency of the structure. This condition occurs when the wind velocity reaches a value equal to the so called critical wind velocity that induces such vortices. Typically the critical wind velocity is a frequent wind velocity, indicating that fatigue may become relevant due to cumulative number and cumulative damage of load cycles.

Boundary Layer and the Separation Phenomenology

The evolution of a standard flow near the solid boundaries is defined as unsteady. The flow along the walls, experience a gradient of considerable speeds dependent on viscosity. The non-slip condition on the border and the presence of significant speeds in the vicinity fosters a significant variation of the speed in a small extension of contours, which interferes with pressure levels that can increase and decrease along the contours.

All this phenomenology (Fig. 1) comes from the influence of viscosity on the movement of fluid particles. Prandl designated this discontinuous region of the flow by boundary layer. This extends from the points of minimum speed (body) to the maximum (flow velocity), extension known as the thickness of boundary layer (Tietjens, 1934) ruled by equations (1) and (2):

\[
\begin{align*}
\frac{\partial v_1}{\partial t} + v_1 \frac{\partial v_1}{\partial x_1} + v_2 \frac{\partial v_1}{\partial x_2} &= - \frac{1}{\rho} \frac{\partial p(x_1, t)}{\partial x_1} + v \frac{\partial^2 v_1}{\partial x_2^2} \\
\frac{\partial v_1}{\partial x_1} + \frac{\partial v_1}{\partial x_2} &= 0
\end{align*}
\]

The velocity within the layer -- equations (1) and (2) -- is \(v_1\), \(v_1\) being the velocity outside. The ratio \(\frac{\partial v_1}{\partial x_1} \cdot \frac{v_1}{L}\) is order of magnitude, where \(L\) is the dimension of the body; \(\frac{\partial v_1}{\partial x_2}\) has the order of magnitude of \(\frac{v_1}{\delta}\), and \(\delta\) the thickness of the boundary layer; \(x_1\) refers to the parallel direction to the border body and \(x_2\) the direction perpendicular.

Fig. 1 - Separation phenomenon of the boundary layer and distribution of pressures; velocity distribution; boundary layer (Freitas 2015, Freitas et al. 2015-a)
Prandtl also found that the movement of a fluid outside the vicinity of solid walls could be represented by an irrotational movement, with negligible viscosity, so that the viscosity only influences inside the boundary layer.

The phenomenon of separation, depicted by the retraction of the flow along the border vicinity, directs the movement of particles towards the outside, causing a deviation of these from the vicinity of the wall, and consequent increase of boundary layer thickness towards downstream. This is associated with the formation of eddies, with considerable energy losses. A delayed flow is established from the point of separation where the increased pressure imposed on particles with low kinetic energy (such energy reserves were spent upstream to overcome the frictional forces in the boundary layer), implements a movement in the opposite direction to the flow. The current flow lines separated from the body surface and forming recirculating bubbles or a wake of eddies. The velocity profiles in the boundary layer analysis shows that this occurs when the curvature near the border is contrary to the outer layer, so there is an inflection point (Tietjens, 1934). The critical velocity of the vortex shedding, is conditioned by the geometry of the restricted element (shape, height, and diameter) and parameters of the flow, the Reynolds number (Re) and Strouhal number (St), which produces variations in the wake pattern.

**Lock-In and Fluid-Structure Interaction**

The lock-in phenomenon arises from a situation of equality of the frequencies: of vortex shedding and of the structure (Simiu, 1996).

The occurrence of vortex shedding characterized by unsynchronized shedding of vortices generates a series of cycles of alternating pressure on the walls of the structure, which is responsible for the appearance of transverse vibrations to the direction of flow. When the shedding frequency of vortices equals the natural frequency of the structure (f) the vibrations increase and the displacements of the structure aggravate, satisfying the equality (3):

$$\frac{fD}{U_{crit}} = St$$

Where $U_{crit}$ is the critical wind velocity, and D is the diameter of the structure.

**Ovalization**

The current trend for tall steel construction of structures with small damping and thin thicknesses, has caused the possibility of occurrence of new problems related with defects at the shell member contours, leading sometimes to the so-called ovalization phenomena. The ovalization can either come from static wind action or from the wind dynamic phenomena. The static ovalization reflects the variation of wind pressures on the shell surface of the cross section (CICIND, 2002). The angular or circumferential distribution of these pressures around the section of a circular tower is represented by expression (4):

$$p_0 = -0.823 + 0.448\cos\Phi + 1.115\cos2\Phi + 0.400\cos3\Phi - 0.113\cos4\Phi - 0.027\cos5\Phi$$

with $p_0 = 0.5\rho v^2$ and $\Phi$ represents the angle between the wind direction and a radial point of the cross section.

The term (- 0.823 $p_0$ ), regardless of the angle of incidence, causes a suction force due to the tension that it imposes along the vertical upstream face. All the other terms represent the pressures in the wind direction, which are responsible for the distortions in the cross section (Fig.2).
The most common is the modification of the circular shape of the section to oval. This transition observed between the base and the top of a tubular tower, together with the longitudinal bending that the tower undergoes along height, is responsible for the alternation of pressures.

The ovalization is not restricted only to cross sections, affecting also the structure at the base level (Fig. 3). For different geometries, heights, velocities and flow directions, the structural behavior changes depending on the stress states generated (CICIND, 2002).

The wind pressure variation along height produces bending moments at the cross sections of cylindrical members. If the wind is applied on the section at an angle $\Phi$, the moment is obtained by equations (5) and (6):

$$m_{0(\max)} = \frac{1.115}{4} \cdot R^2 \cdot p_o \cdot \cos 2\Phi$$  \hspace{1cm} (5)

with a maximum observed for:

$$m_{0(\max)} = 0.07 \cdot p_o \cdot D^2$$  \hspace{1cm} (6)

where $1/R$ is the curvature of the element due to the effect of wind pressure on the mast.
Stability – Geometry Changes

The use of aerodynamic devices arises with the demand for a methodology of simple execution who can ensure an adequate structural operation during the period corresponding to the structure life cycle.

The primary goal focuses on the control of the vibrations induced by the flow, and may include cases of structures still in the design phase or of structures already in operation.

Zdravkovich (1981) has distinguished a number of aerodynamic methodologies (represented in Fig. 4), divided into three categories. The first is restricted to surface protrusions, the second are shrouds, and the third category details near-wake stabilizers.

The surface protrusions, was further subdivided into two sub-categories, in order to separate the omnidirectional solutions from the unidirectional ones. The two subdivisions, with representative types, are:

- omnidirectional methodologies, which are not affected by the direction of fluid velocity (Fig. 4 - i (a) ): helical strakes or straps (1); helical wires (2); rectangular plates forming a helix (5), helical wires forming a herringbone pattern (6);
- unidirectional methodologies, which are effective only in one direction of velocity as shown in (Fig. 4 - i (b) ): four straight fins forming an × cross (7); staggered straight wires (10); staggered rectangular fins (11); small spheres as turbulence promoters (12).

The second category covers all possible shapes of shrouds. The full shrouds are omnidirectional but when incomplete they become unidirectional means. The following types of shrouds have been developed (Fig. 4 - ii): fine mesh gauze used as a shroud (14); parallel axial rods forming a shroud (15); "shroud" reduced to four rods (17); shroud consisting of straight slats (18).

The near-wake stabilizers encompasses a wide variety of methodologies that possess only unidirectional effectiveness (Fig. 4 - iii): saw-tooth fins (19); detached splitter plate (20); guiding plates (21); guiding vanes (22); base-bleed into the near-wake (blunt airfoil) (23); slit along the cylinder (24).

Helicoid Straps Design

Constituting no more than surface protrusions in helical shape, the helical strakes (helicoid straps) are added around the structure and are characterized by the: pitch "p", number of helices "n", height or thickness of the protrusions t and diameter of the structure “D”. Their function presupposes the production of such an interference, at the level of the wake, able to act on the boundary layers in order to suppress the effects of the vortices for certain flow conditions. Another factor of great importance is the control and prevention of fatigue, resulting from strong vibrations or from cumulative damage of standard vibrations along life-cycle.

Despite the extremely efficient behavior provided by the strakes solution, proven by successive studies, the methodology of the strakes is lacking more studies regarding the increase of the drag coefficient. In Fig. 5, it is observed that more stable scenario for wind speeds corresponding to lower St (or, higher 1/St) the most effective and stable solutions are those that comprise a more significant strake device.

The extensive experimentation led to the development of an ideal strake (strap) concept, which has a pitch between 4D and 5D, and a minimum thickness t for effective suppression of vibration given by t = 0,08 D (Freitas et al. 2015-a).
Fig. 4 - Interventions in structural geometry mitigating effect of structural vibrations;  
i- surface protrusions:  
a) omnidirectional; b) unidirectional; ii- shrouds; iii- near-wake stabilizers  (Zdravkovich, 1981)
Eurocode Approach for Vortex Shedding

As previously perceived the vortex shedding phenomenon occurs for a wind speed designated by critical velocity. Due to its adverse nature, a good structural integrity should be achieved through an adequate design preventing such occurrence. Annex E of NP EN 1991-1-4 2010 describes two procedures to check this phenomenon. The effect of vortex shedding should be investigated when the ratio of the largest to the smallest crosswind dimension of the structure, both taken in the plane perpendicular to the wind, exceeds 6. The effect of vortex shedding needs not be investigated when expression (7) is satisfied:

$$v_{crit} > 1.25v_m$$

(7)

$v_{crit}$ is the critical wind velocity for mode $i$; $v_m$ is the characteristic 10 minutes mean wind velocity at the cross section where vortex shedding may occur.

The critical wind velocity for bending vibration mode $i$ is defined as the wind velocity at which the frequency of vortex shedding equals a natural frequency of the structure or a structural element and is given in equation (8):

$$v_{crit} = \frac{b \cdot n_{i,y}}{St}$$

(8)

$b$ is the reference width of the cross-section at which resonant vortex shedding occurs and where the modal deflection is maximum for the structure or structural part considered (for circular cylinders the reference width is the outer diameter); $n_{i,y}$ is the natural frequency of the considered flexural mode $i$ of cross-wind vibration; $St$ is Strouhal number as defined in Fig. 6 (section E.1.3.2 of EN 1991-1-4).
The critical wind velocity for ovalization of the vibration mode \( i \) of cylindrical shells is defined as the wind velocity causing vibrations of the ovalling mode \( i \) of the cylindrical shell at natural frequency of ovalling which is two times of the frequency of vortex shedding; it is given in equation (9).

\[
v_{\text{crit}} = \frac{b \cdot n_{i,o}}{St}
\]  

(9)

\( n_{i,o} \) is the natural frequency of the considered ovalling mode \( i \) of cross-section.

For the consideration of the vortex shedding effect the calculation of the Reynolds number uses the critical wind velocity (Barros, 2002) as in equation (10).

\[
Re(v_{\text{crit}}) = \frac{b \cdot v_{\text{crit}}}{v}
\]  

(10)

The effect of vibrations induced by vortex shedding should be calculated from the effect of the inertia force per unit length \( F_{w(s)} \), acting perpendicular to the wind direction at location \( s \) on the structure and given in equation (11).

\[
F_{w,\text{vortices}} = m(s) \cdot (2 \pi n_{i,y})(s) \cdot \Phi_{i,y}(s) \cdot y_{F,max}
\]  

(11)

where \( m(s) \) is the vibrating mass of the structure per unit length [kg/m]; \( \Phi_{i,y}(s) \) is the mode shape of the structure normalized to 1 at the point with the maximum displacement; \( y_{F,max} \) is the maximum displacement over time of the point with \( \Phi_{i,y}(s) \) equal to 1 (section E.1.5 of EN 1991-1-4). Two different approaches for calculating the vortex excited cross-wind amplitudes \( y_{F,max} \) mentioned above) are given in Eurocode: approach 1 and approach 2.

**Approach 1**

The largest displacement \( y_{F,max} \) can be calculated using equation (12):

\[
y_{\text{max}} = \frac{1}{St^2} \cdot \frac{1}{Sc} \cdot KK_w \cdot c_{lat}
\]  

(12)

where \( K_w \) is the effective correlation length factor; \( K \) is the mode shape factor; \( c_{lat} \) is the lateral force coefficient. The basic value, \( c_{lat,0} \) of the lateral force coefficient is given in Fig. 7.

![Fig. 7 - Basic value of the lateral force coefficient \( c_{lat,0} \) versus Reynolds number Re(vcrit,i) for circular cylinders, (EN1991-1-4)]
From the ratio between the critical wind velocity and the average velocity at the top of the tower level, is determined the lateral coefficient $c_{lat}$ from equation (13).

$$
c_{lat} = \begin{cases} 
    c_{lat, 0}, & \frac{v_{crit}}{v_{m, i, j}} < 0.83 \\
    3 - 2.4 \frac{v_{crit}}{v_{m, i, j}} c_{lat, 0}, & 0.83 < \frac{v_{crit}}{v_{m, i, j}} < 1.25 \\
    0, & 1.25 < \frac{v_{crit}}{v_{m, i, j}} 
\end{cases}
$$

(13)

The determination of the coefficient of correlation length needs prior knowledge of the correlation length $L$ (see Figure E.3 EN1991-1-4). For this, the European norm suggests the adoption of a structure type associated with an expert opinion.

The effective correlation length factor, $K_W$, is given in expression (14):

$$
K_W = \left. \frac{\sum_{j=1}^{n} \int_{l_j} |\phi_{i,j}(s)| \, ds}{\sum_{j=1}^{m} \int_{l_j} |\phi_{i,j}(s)| \, ds} \right| \leq 0.6
$$

(14)

$l_j$ is the length of the structure between two nodes; $n$ is the number of regions where vortex excitation occurs at the same time; $m$ is the number of anti-nodes of the vibrating structure in the considered mode shape; $s$ is the coordinate corresponding to evolution along the height of the structure.

Cylindrical towers with characteristic vibration of the fundamental mode, the wind direction to the transverse direction the effective correlation length factor $K_W$ can be determined by:

$$
K_W = \frac{L_j/b}{\lambda} \left[ 1 - \frac{L_j/b}{\lambda} + \frac{1}{3} \left( \frac{L_j/b}{\lambda} \right)^2 \right]
$$

(15)

The mode shape factor $K$ is given by equation (16). However it can be assumed as $K = 0.13$ in some structures, as indicated in Table E.5 NP EN 1991-1-4.

$$
K = \frac{\sum_{j=1}^{m} \int_{l_j} |\phi_{i,j}(s)| \, ds}{4.\pi \sum_{j=1}^{m} \int_{l_j} \phi_{i,j}^2(s) \, ds}
$$

(16)

**Approach 2**

The characteristic maximum displacement at the point with the largest movement is given by equation (17):

$$
y_{max} = \sigma_y \cdot k_p
$$

(17)

$\sigma_y$ is the standard deviation of the displacement, $k_p$ is the peak factor.

The standard deviation $\sigma_y$ of the displacement, related to the width $b$ at the point with the largest deflection ($\Phi = 1$), can be calculated by using equation (18).

$$
\frac{\sigma_y}{b} = \frac{1}{St^2} \sqrt{\frac{C_e}{S_{c} - K_c \cdot (1 - (\frac{\sigma_y}{b \cdot a_v})^2)}} \cdot \sqrt{\frac{\rho \cdot b^2}{m_e} \cdot \frac{h}{b}}
$$

(18)
Cc is the aerodynamic constant dependent on the cross-sectional shape, and for a circular cylinder also dependent on the Reynolds number Re; \( K_a \) is the aerodynamic damping parameter; \( a_k \) is the normalised limiting amplitude giving the deflection of structures with very low damping; \( \rho \) is the air density under vortex shedding conditions; \( m_e \) is the effective mass per unit length. Figure 8, taken from the European norm, those constants are shown.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Circular cylinder</th>
<th>Circular cylinder</th>
<th>Circular cylinder</th>
<th>Square cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>0,02</td>
<td>0,005</td>
<td>0,01</td>
<td>0,04</td>
</tr>
<tr>
<td>( K_{a,max} )</td>
<td>7</td>
<td>0,5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>( a_k )</td>
<td>0,4</td>
<td>0,4</td>
<td>0,4</td>
<td>0,4</td>
</tr>
</tbody>
</table>

**NOTE:** For circular cylinders the constants \( C_c \) and \( K_{a,max} \) are assumed to vary linearly with the logarithm of the Reynolds number for \( 5 \times 10^4 < Re < 5 \times 10^5 \) and for \( 5 \times 10^5 < Re < 5 \times 10^6 \), respectively.

Fig. 8 - Constants for determination of the effect of vortex shedding

The solution to equation (18) is given by equation (19)

\[
\left( \frac{\sigma}{B} \right)^2 = c_1 + \sqrt{c_1^2 + c_2}
\]

(19)

in which the quantities \( c_1 \) and \( c_2 \) are given in the following equations (20) and (21):

\[
c_1 = \frac{a_k^2}{2} \left( 1 - \frac{Sc}{4. \pi. K_a} \right)
\]

(20)

\[
c_2 = \frac{\rho b^2}{m_e} \cdot \frac{C_c^2}{K_a} \cdot \frac{b}{St^2 \cdot h}
\]

(21)

The peak factor \( k_p \) should be determined according with equation (22)

\[
k_p = \sqrt{2} \times \left\{ 1 + 1,2 \times \arctan\left( 0,75 \frac{Sc}{4. \pi. K_a} \right) \right\}
\]

(22)

As mentioned earlier the number of Scruton is obtained by the expression:

\[
Sc = \frac{2 \delta m_{i,e}}{\rho b^2}
\]

(23)

\( \delta \) is the structural damping expressed by the logarithmic decrement (defined in Annex F5 of EN1991-1-4); \( m_{i,e} \) is the equivalent mass \( m_e \) per unit length for mode \( i \) (defined in Annex F4 (1), of EN1991-1-4)

Aerodynamic methodologies in order to mitigate the effect of vortex shedding, more specifically the introduction of helical strakes, are taken into account in calculating the vibrations effects by using the multiplication of the coefficient \( C_{LAT} \) by the coefficient \( \alpha \), referred to in Annex B (2) EN 1993-3-2:

\[
\alpha = \left( 1 - \frac{l_s}{h} \right)^3
\]

(24)

\( l_s \) is the length of the shell fitted with strakes; \( h \) is the total height of the chimney.
This coefficient should only be used provided the geometry of such helical strakes is as follows:

- three start strakes;
- pitch of the strakes \( h_s = 4.5 \, D \) to \( 5 \, D \), where \( D \) is the diameter of the mast;
- depth of the strakes \( t = 0.10 \, D \) to \( 0.12 \, D \);
- strakes extend over a length \( l_s \) of at least 0.3 \( h \), and normally between 0.3 \( h \) and 0.5 \( h \).

However a top portion not exceeding 1.0 \( D \) with no strakes is permitted, and may be included in the length \( l_s \) in equation (24).

In the above it is assumed that Approach 1 of Annex E to EN 1991-1-4 is used. However, within this paper the same procedure was applied identically in Approach 2. In the calculation of cross-wind amplitudes a correlation length factor \( K_w \) of 1.0 is assumed. The provision of strakes or shrouds will increase the drag factor of the chimney section on which they are mounted. For strakes whose height (or depth) is up to 0.2 times the chimney diameter, the drag factor should be taken as \((1.2)\) on the overall diameter (i.e., including the height or depth of the strakes).

**CFD ANALYSIS OF A TELECOMMUNICATION TOWER**

The Domain control is the first step for simulation the flow around the cylinder using a CFD (computational fluid dynamics) software. In this situation CFD will play the role of a wind tunnel function in which the tower is supposed to be centered. Starting with standardized dimensions (similar to older study cases used in other master of science thesis, also supervised by the second co-author), the dimensions taken safeguard the correct interpretation of the flow phenomena around the tower section.

The 3D wind flow across the 22 m height tubular tower was modelled in Ansys Fluent software using a 3D-mesh with dimensions, across de tower, of 7\( D \) by 11\( D \) (Figure 9).

The meshing (Fig. 10) is provided by Ansys Fluent software in the Mesh menu. The ability to set criteria and parameters allows the improvement of the final quality of the mesh and thus obtain more reliable results. The applied method was the "Cut-Cell". This includes rectangular elements, of increased efficiency in refining and processing (Freitas, 2015).
Flow Characteristics and Boundary Conditions

The fluid in analysis is air, in the incompressible state, and properties are shown in Table 1.

<table>
<thead>
<tr>
<th>Fluid Properties</th>
<th>Volumic Mass (kg/m³)</th>
<th>Viscosity (Pa.s)</th>
<th>Velocity (m/s)</th>
<th>Initial turbulence intensity (%)</th>
<th>Viscosity Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1,225</td>
<td>1,5 E⁻⁵</td>
<td>13,467</td>
<td>0,8</td>
<td>1</td>
</tr>
</tbody>
</table>

A turbulence intensity default by Ansys Fluent of 0.8% was chosen, instead of the value determined by the Eurocode and calculated as 0.3%. This consideration is conservative, since a greater turbulence intensity provokes a more devastating effect on the structure. In correspondence with the idealized scenario for the flow around the tower, the boundaries of the volume control were defined (as in Fig. 11). To do this, Ansys Fluent uses a specific code of words: most notably the terms INLET, OUTLET, SYMMETRY, BODY and WALL.
The used method for calculation of the solution is the SIMPLE (Semi Implicit Method for Pressure-Linked Equations). This develops algebraic equations of flow, interrelating velocity and pressure corrections that enhance the conservation of mass. Its procedure allows the correct discretization of the terms involved. The discretization conditions applied (Table 2) were:

### Table 2 - Applied conditions - Ansys

<table>
<thead>
<tr>
<th></th>
<th>Gradient</th>
<th>Pressure</th>
<th>Moment</th>
<th>Turbulent kinetic energy</th>
<th>Turbulent dissipation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Least Squares Cell Based</td>
<td>Standard</td>
<td>Second Order Upwind</td>
<td>Second Order Upwind</td>
<td>Second Order Upwind</td>
</tr>
</tbody>
</table>

### Flow Conditions

In the performed CFD analysis two types of flow were considered: (a) A horizontal steady stream flow with average velocity $v_m = 13$ m/s close to the critical wind velocity of the tower; (b) A variable flow, with velocity in height ($z$) varying according to the equation (25):

$$v_m(z) = 0.010784496z^2 + 0.005027253z + 15.28106475$$

(25)

The turbulent model applied was the k-ε. The methodology comprises the resolution of two transport equations that represent the turbulence of the flow which enhances the consideration of the effects of convection, diffusion and energy dissipation. The variable $k$ is related to the turbulent kinetic energy and $ε$ is the turbulent kinetic energy dissipation rate. Within this model there are three formulations: Standard, Renormalized (RNG) and Realizable, deriving from each other by an evolutive process (White, 2003).

### Simulation and Data Analysis

Along with the simulation via CFD a calculation process was completed according with the rules of EN 1991-1-4 through **approach 1** and **approach 2**. For the results obtained, either for the critical wind or for the variable velocity profile in height, the Reynolds numbers found belong to a turbulent regime, which is an essential condition for the follow up of simulations with the model k-ε. The values of the relevant calculation parameters are expressed in Tables 3 and 4. The time-consuming software analysis led to consider only the variable velocity in height as a scenery for simulating the towers with strakes solutions.

### Table 3 - Parameters of the average calculation values - simple tower

<table>
<thead>
<tr>
<th>$A_{ref}$(m$^2$)</th>
<th>$v_{top}$ (m/s)</th>
<th>Re</th>
<th>$c_D$</th>
<th>$c_\epsilon$</th>
<th>$C_D$</th>
<th>$C_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>26,4</td>
<td>13</td>
<td>1,86E+06</td>
<td>0,75</td>
<td>0,56938</td>
<td>0,2</td>
<td></td>
</tr>
<tr>
<td>26,4</td>
<td>20,27</td>
<td>2,46E+06</td>
<td>0,77</td>
<td>0,58385</td>
<td>0,2</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4 - Parameters of the average calculation values - tower with strakes

<table>
<thead>
<tr>
<th>$A_{ref}$(m$^2$)</th>
<th>$v_{top}$ (m/s)</th>
<th>Re</th>
<th>$c_D$</th>
<th>$c_\epsilon$</th>
<th>$C_D$</th>
<th>$C_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27,38</td>
<td>20,27</td>
<td>2,46E+06</td>
<td>0,77</td>
<td>0,58385</td>
<td>0,0432</td>
<td></td>
</tr>
</tbody>
</table>

$C_D$ is the drag coefficient $C_l$ and the lateral force coefficient. For the calculation of the (drag or lift) coefficients, from the forces obtained by the Ansys Fluent turbulence model, it was considered the following equation (26) where $v_{top}$ speed corresponds to the height of 22 m.

$$C_{D\ ou\ L} = \frac{F_{D\ ou\ L}}{\frac{1}{2} \rho_{\infty} U^2 A_{ref}}; U^2 = v_{top}^2$$

(26)
The set of towers in this study was composed of: tower, tower with minimum geometry strakes solution, tower with medium geometry strakes solution and tower with maximum geometry strakes solution. Worth noting is that the aerodynamic methodologies used to mitigate the effect of vortex shedding, more specifically the introduction of helical strakes, are taken into account in calculating reduced vibration forces by the multiplication of the coefficient $C_{lat}$ by $\alpha$ coefficient (as already mentioned in this paper, when using equation (24)).

**Results and Conclusions of the Computational Study**

The first step was the assessment of the drag and lateral force coefficients for each scenario of the incident wind in the tower. Fig. 12 shows the two cases for the tower without strakes.

Worth mentioning is the nonconformity of the situation of wind constant velocity in height with reality (Table 5). This distorts the interpretations of the results, appearing even anomalous values of $C_L$ in this scenario. Giving relevance to the variable velocity profile the $C_D$ obtained are close to the ones obtained with EN1991-4, on the other hand the $C_L$ only appear as reasonable in Standard and Realizable model (Freitas, 2015).

<table>
<thead>
<tr>
<th>Turbulence model</th>
<th>Constant velocity</th>
<th>Variable velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_D$</td>
<td>$C_L$</td>
</tr>
<tr>
<td>K-\varepsilon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>1,052746</td>
<td>0,00007</td>
</tr>
<tr>
<td>RNG</td>
<td>0,971077</td>
<td>-0,00004</td>
</tr>
<tr>
<td>Realizable</td>
<td>0,983807</td>
<td>0,00006</td>
</tr>
<tr>
<td>Values using EC1 (Part 1.4)</td>
<td>0,56938</td>
<td>0,2</td>
</tr>
</tbody>
</table>

For a wind flow with constant velocity along height, three configurations of helicoid strakes were considered with 3 specific sets of variables: a minimum step-size of helicoid strakes, medium size of helicoid strakes and maximum size of helicoid strakes (Table 6).
The results for lateral and drag coefficients evaluated by CFD modelling are compared in Table 7 with those corresponding values obtained by EN 1991-1-4 and EN 1993-3-2.

Table 6 - Strakes geometry

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Strakes representation</th>
<th>p</th>
<th>e</th>
<th>l,</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td></td>
<td>4,5D</td>
<td>0,1D</td>
<td>0,3h</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>4,75D</td>
<td>0,11D</td>
<td>0,4h</td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
<td>5D</td>
<td>0,12D</td>
<td>0,5h</td>
</tr>
</tbody>
</table>

Table 7 - Drag and lateral coefficients for the 3 parametric geometric cases considered in the CFD study

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Turbulence model</th>
<th>CD</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>Standard</td>
<td>0,73951</td>
<td>0,07715</td>
</tr>
<tr>
<td>Medium</td>
<td>RNG</td>
<td>0,74379</td>
<td>0,04456</td>
</tr>
<tr>
<td>Maximum</td>
<td>K-ε</td>
<td>0,79573</td>
<td>0,14224</td>
</tr>
</tbody>
</table>

Values obtained by EC1 (Part 1.4) and by EC3 (EN 1993-3-2)

<table>
<thead>
<tr>
<th>CD</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,58385</td>
<td>0,0432</td>
</tr>
</tbody>
</table>

Proportional to the evolution of geometry strakes (from minimum to maximum) it should be also emphasized the increase in the tower exposed area associated also with the increase of CD drag coefficients. The analysis of the values in Table 7 confirms the assumption made relating the higher CD values occurring for towers of maximum strake geometry. The majority of the lateral force coefficients approximate the Eurocode results. The following average coefficients were calculated $C_D = 0.7597156$ and $C_L = 0.050577514$.

With regards to minimum error in evaluating the lift coefficient $C_L$, it follows that the medium geometry strakes are the best choice, case for which the drag coefficient $C_D$ becomes also very close to the average calculated value. The optimal geometry for both $C_L$ and $C_D$ evaluations occur in the Realizable Turbulent Model K-ε, characterized to be the more accurate and reliable model because of being derived from the others (Freitas 2015).

CONCLUSIONS

Some theoretical concepts and regulatory dispositions were reviewed associated with the design of helicoidal strakes (helicoid straps) for tubular telecommunication towers. Additionally, in this paper $C_D$ and $C_L$ coefficients of a specific tower were obtained using the
CFD formulation inherent in Ansys Fluent. Such values were compared the values evaluated with the Eurocodes standards 1 and 3. The differences are of the order of 31% for $C_D$ and 5% for the $C_L$.

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REFERENCES